Dark Matter Search with the CDMS Experiment

Sebastian Arrenberg
University of Zürich
for the CDMS Collaboration
DPNC, University of Geneva, September 21st, 2011

The CDMS Collaboration

California Institute of Technology
Z. Ahmed, J. Filippini, S.R. Golwala, D. Moore, R.W. Ogburn

Case Western Reserve University
D. Akerib, C.N. Bailey, M.R. Dragowsky,
D.R. Grant, R. Hennings-Yeomans

Fermi National Accelerator Laboratory
D. A. Bauer, F. DeJongh, J. Hall, D. Holmgren,
L. Hsu, E. Ramberg, R.L. Schmitt, R. B. Thakur, J. Yoo

Massachusetts Institute of Technology
A. Anderson, E. Figueroa-Feliciano, S. Hertel,
S.W. Leman, K.A. McCarthy, P. Wikus

NIST
K. Irwin

Queen's University
P. Di Stefano , C. Crewdson , J. Fox ,
S. Liu , C. Martinez, P. Nadeau , W. Rau, Y. Ricci

Santa Clara University
B. A. Young

Southern Methodist University
J. Cooley, B. Karabuga, H. Qiu

SLAC/KIPAC
M. Asai, A. Borgland, D. Brandt, W. Craddock, E. do Couto e Silva,
G.G. Godfrey, J. Hasi, M. Kelsey, C. J. Kenney, P. C. Kim,
R. Partridge, R. Resch, D. Wright

Stanford University
P.L. Brink, B. Cabrera, M. Cherry , R. Moffatt, L. Novak,
M. Pyle, M. Razeti, B. Shank, A. Tomada, S. Yellin, J. Yen

Syracuse University
M. Kos, M. Kiveni, R. W. Schnee

Texas A&M
A. Jastram, K. Koch, R. Mahapatra, M. Platt , K. Prasad, J. Sander

University of California, Berkeley
M. Daal, T. Doughty, N. Mirabolfathi, A. Phipps, B. Sadoulet,
D. Seitz, B. Serfass, D. Speller, K.M. Sundqvist

University of California, Santa Barbara
R. Bunker, D.O. Caldwell, H. Nelson

University of Colorado Denver
B.A. Hines, M.E. Huber

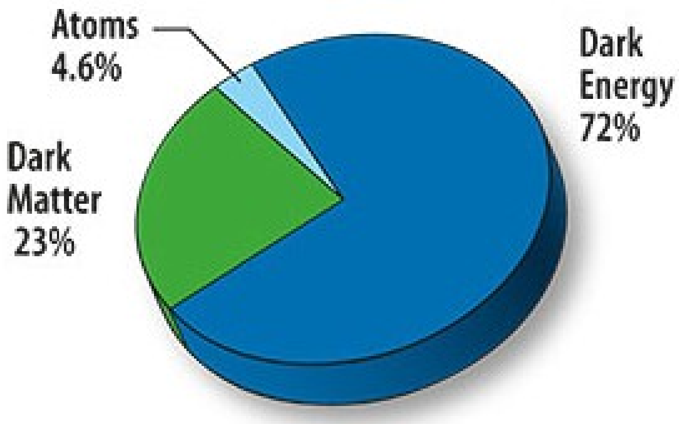
University of Florida
T. Saab, D. Balakishiyeva, B. Welliver

University of Minnesota
J. Beaty, H. Chagani, P. Cushman, S. Fallows, M. Fritts,
O. Kamaev, V. Mandic, X. Qiu, A. Reisetter, J. Zhang

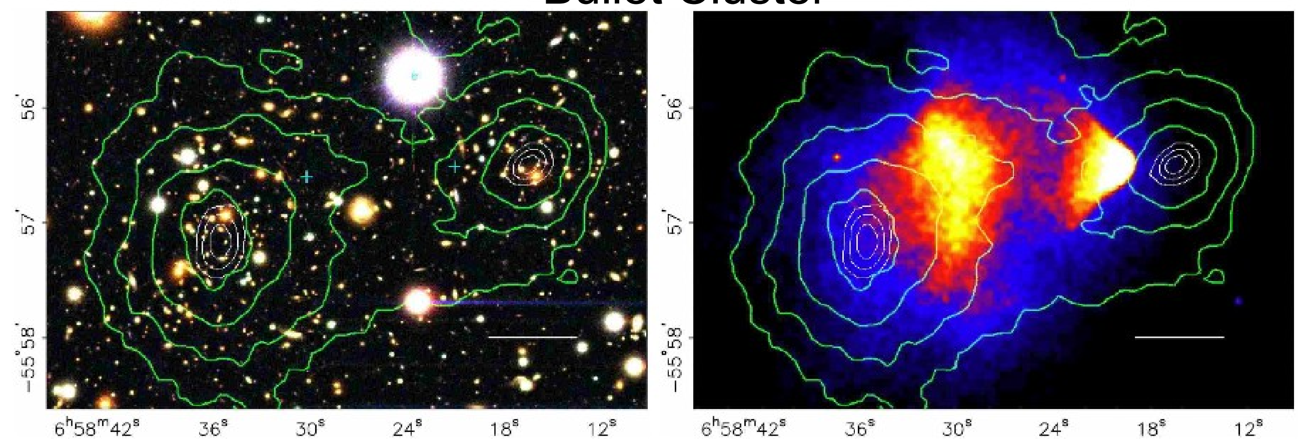
University of Zurich
S. Arrenberg, T. Bruch, L. Baudis, M. Tarka

Dark matter and direct detection

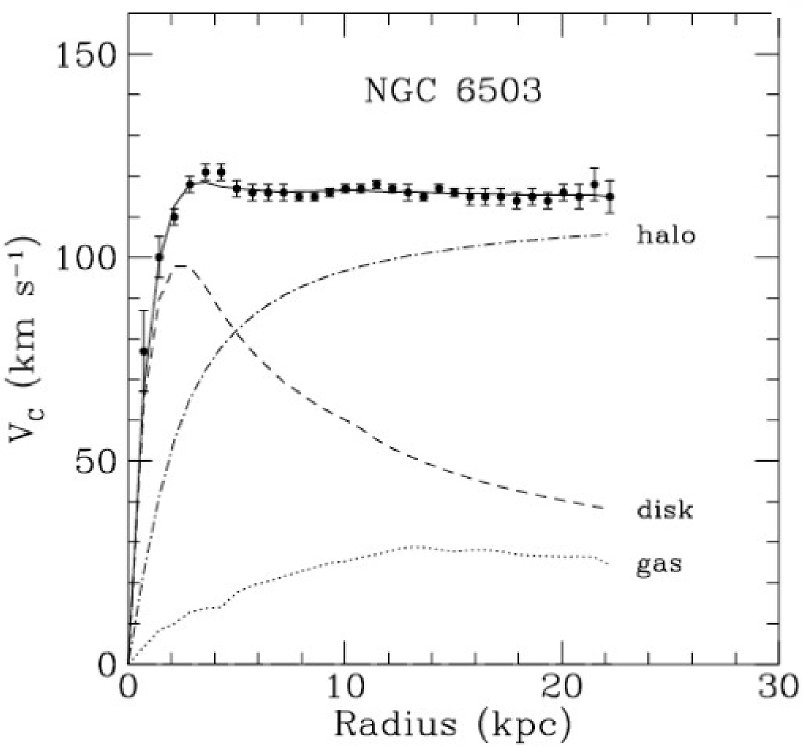
Cosmological observations



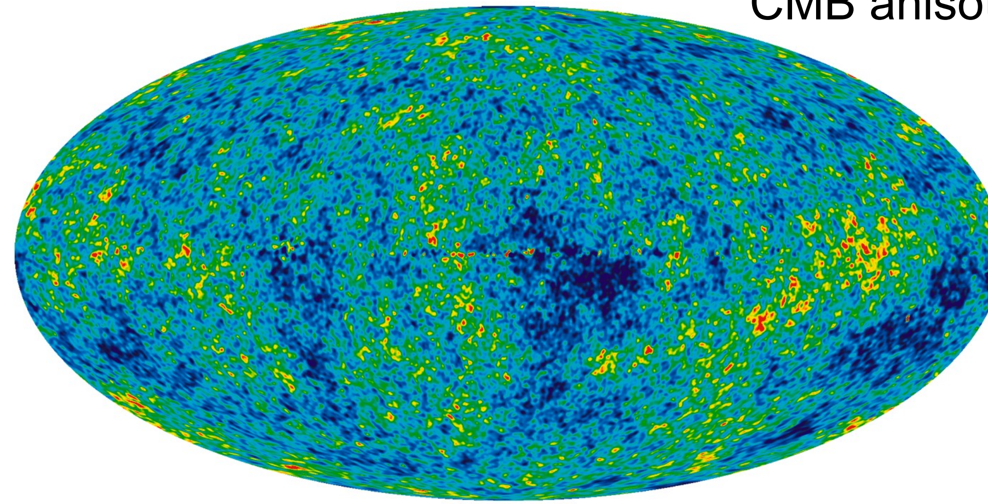
Bullet Cluster



rotation curves

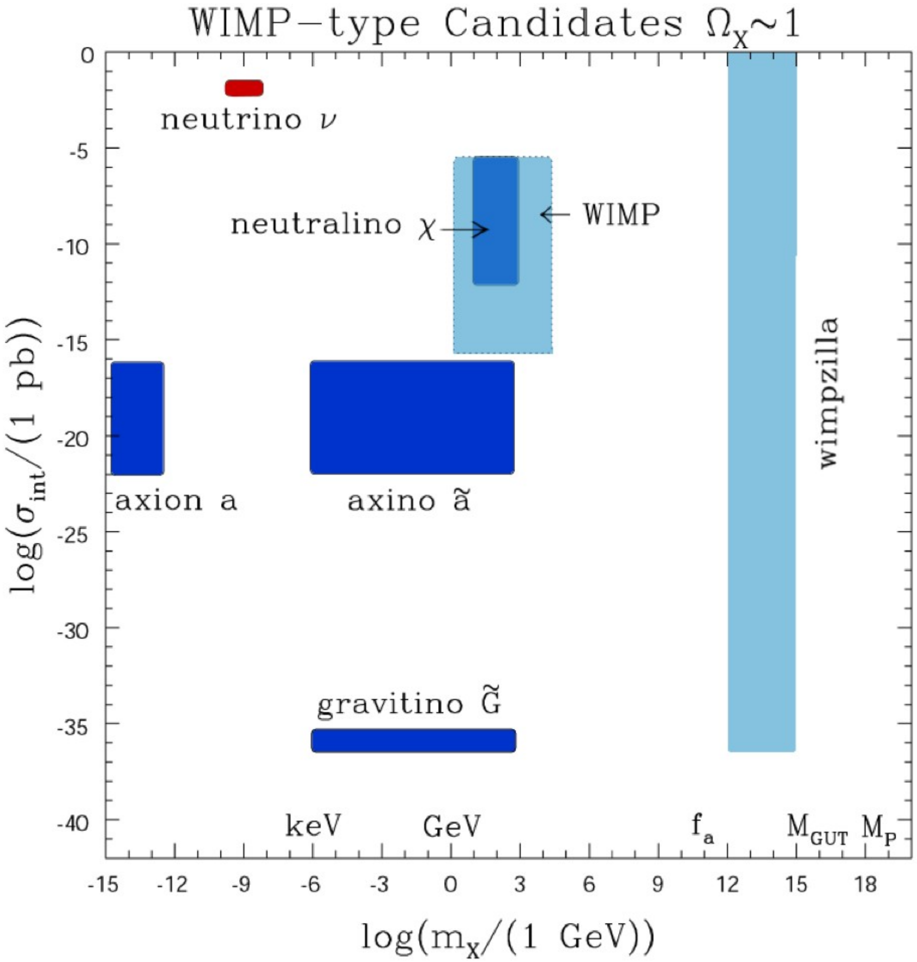


CMB anisotropies



Dark Matter and WIMPs

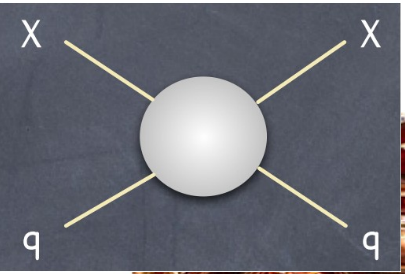
We “know“ that dark matter is
- non-baryonic
- cold (structure formation)
- does not emit or absorb light
- not strongly interacting
- stable



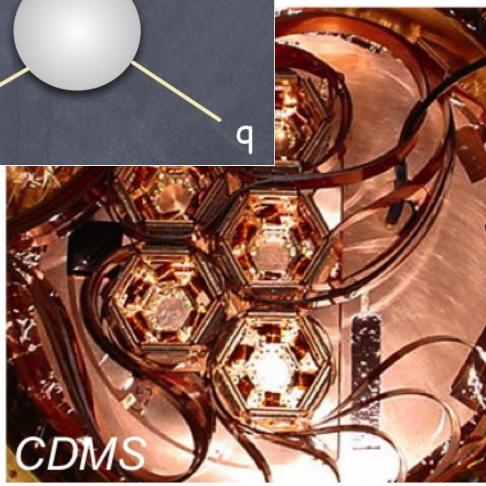
We do not know the
- mass
- cross section (interaction with matter, self-annihilation)

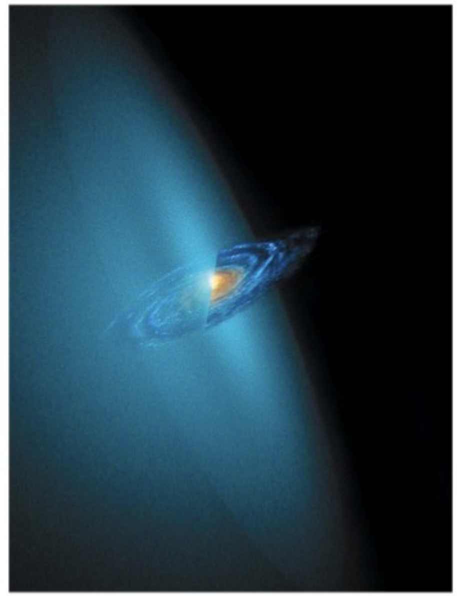
Weakly Interacting Massive Particle (WIMP) is a prominent dark matter candidate
- stable, massive particle produced thermally in the early universe
- produced with the correct thermal relic density
- weak-scale interaction cross sections
- arises naturally in various well-motivated extensions of the Standard Model (SUSY, UED, …)

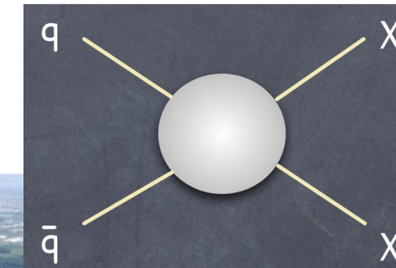
How can WIMPs be detected?

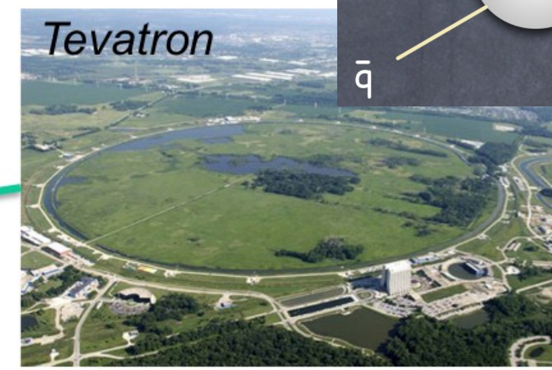


WIMP scattering on earth

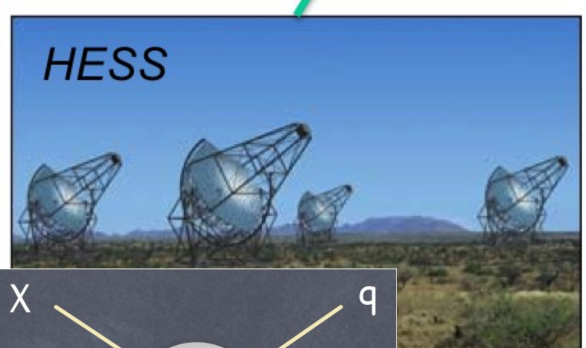


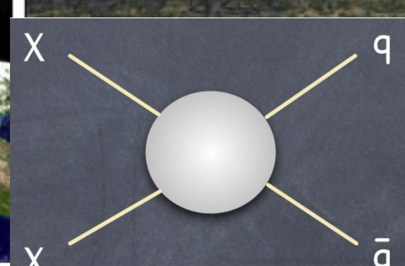






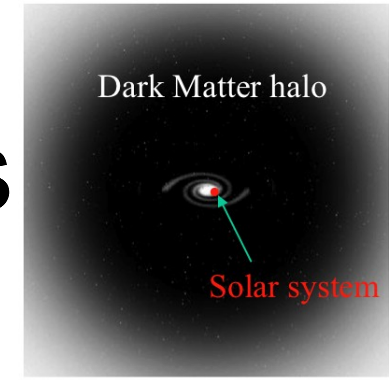
WIMP production on earth



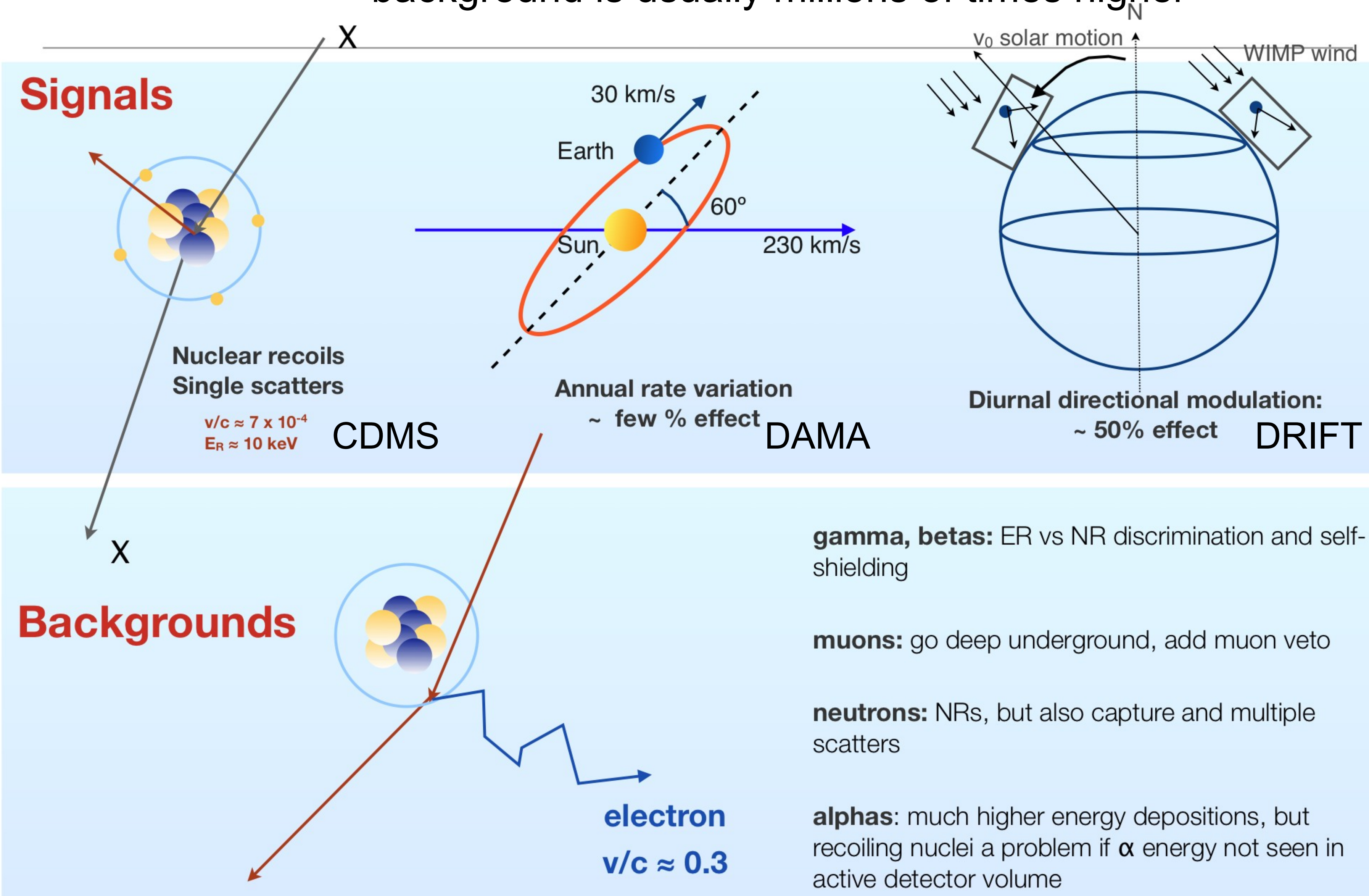


WIMP annihilation in the cosmos

Direct Detection of WIMPs



Main challenges:
- signal is very small (~keV)
- rare events (1 per ton per year?)
- background is usually millions of times higher



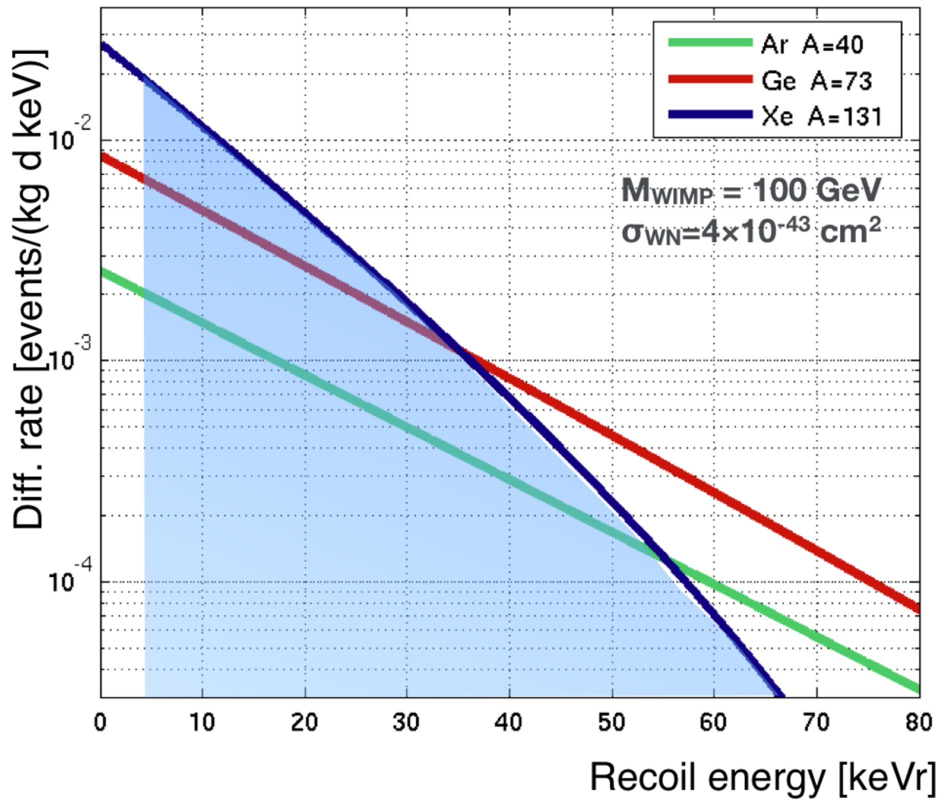
Direct Detection of WIMPs

- elastic collisions with atomic nuclei

- differential rate depends on WIMP-velocity distribution, local WIMP density, target nuclei, threshold, atomic form factor, WIMP mass, WIMP-nucleon cross section

$$\frac{dR}{dE_R} = \frac{\sigma_0 \rho_0}{2 m_\chi \mu^2} F^2(E_R) \int_{v_{min}}^{v_{max}} \frac{f(v)}{v} dv$$

- assuming Maxwellian-velocity distribution → featureless nearly exponential spectrum



- WIMP scattering can be classified as:
  - spin-independent (scalar) interaction (WIMP couples to nuclear mass m_n)

$$\sigma_{SI} = \frac{m_N^2}{4\pi(m_\chi + m_N)^2}\left[Z f_p + (A-Z) f_n\right]^2$$

  - spin-dependent interaction (WIMP couples to nuclear spin J_n)

$$\sigma_{SD} = \frac{32}{\pi} G_F^2 \frac{m_\chi^2 m_N^2}{(m_\chi + m_N)^2} \frac{J_N + 1}{J_N} \left(a_p \langle S_p \rangle + a_n \langle S_n \rangle\right)^2$$

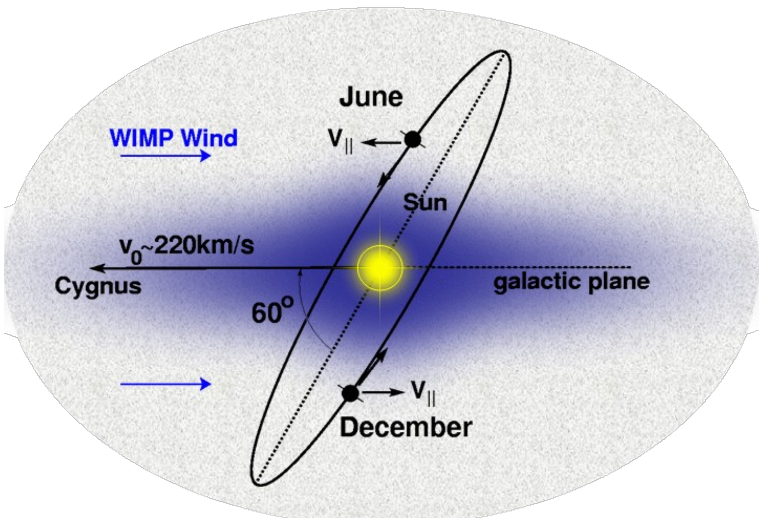
f_p,f_n,a_p,a_n are effective couplings to protons and neutrons

DAMA/LIBRA and inelastic dark matter

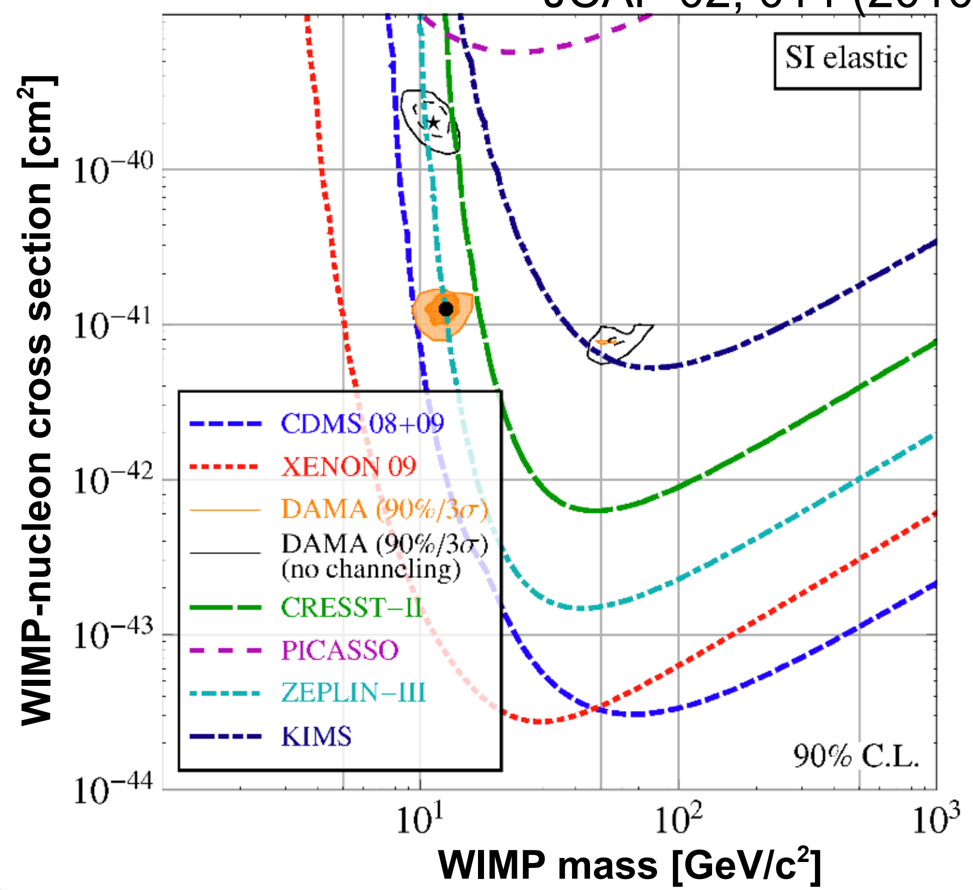
The DAMA/LIBRA results

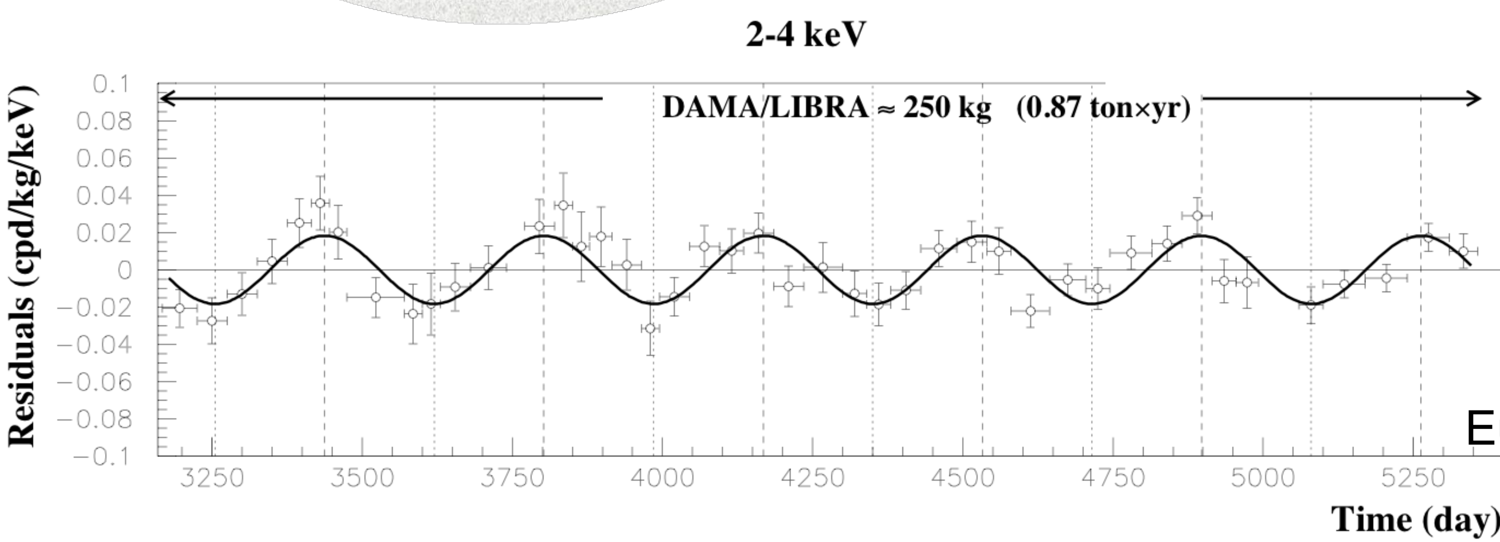
- observation of annual modulation at low recoil energies (2 – 4 keV)

- evidence @ 8.9σ C.L.



JCAP 02, 014 (2010)





Eur. Phys. J. C 67, 39 (2010)

Inelastic Dark Matter (IDM)

Phys. Rev. D 64, 043502 (2001)

- 2 dark matter states with mass splitting δ ~100 keV

- WIMP-nucleus scattering through transition of WIMP into excited state WIMP*

$$\chi N \rightarrow \chi^* N$$

- elastic scattering forbidden or highly supressed

- minimum velocity is increased

$$v_{\min} = \frac{1}{\sqrt{2 m_T E_{\text{rec}}}} \left(\frac{m_T E_{\text{rec}}}{\mu} + \delta \right)$$

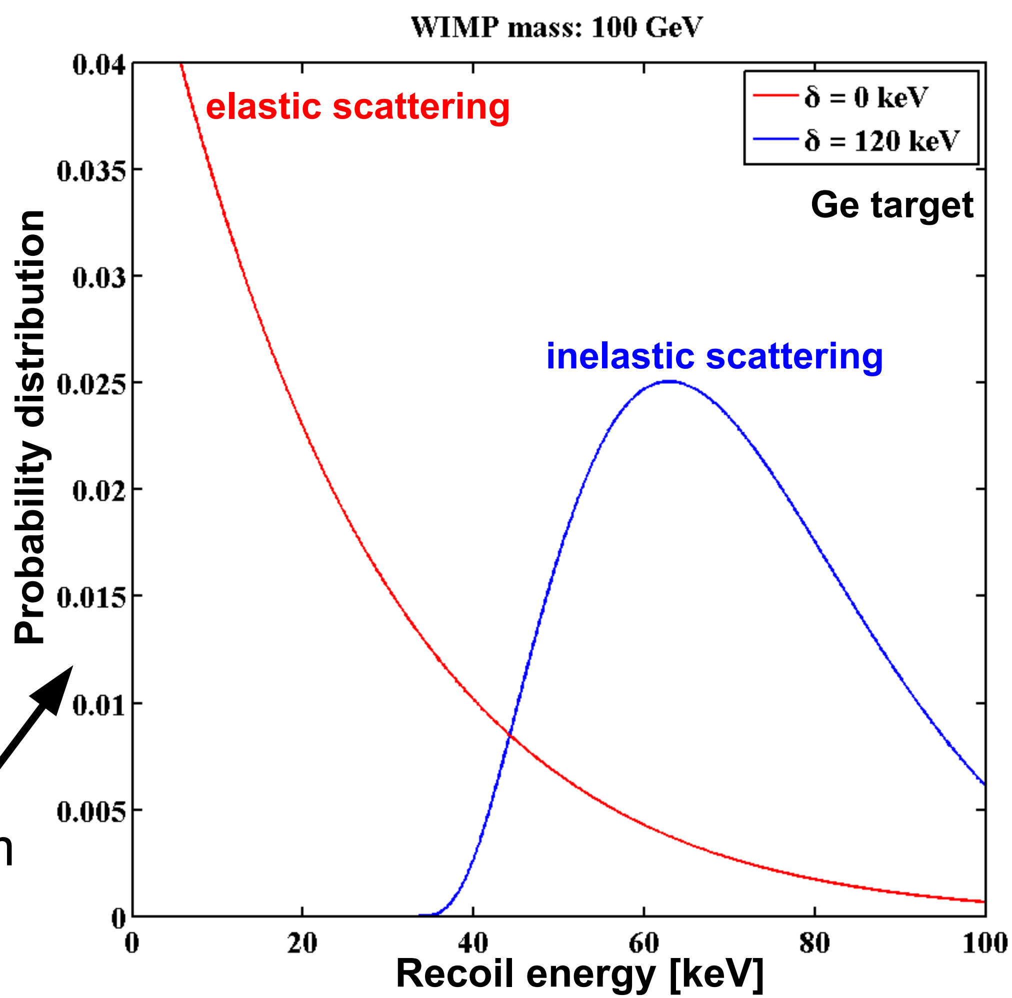
- experiments probe “higher“ part of velocity distribution

- high sensitivity to escape-velocity cutoff

- heavy targets are favoured

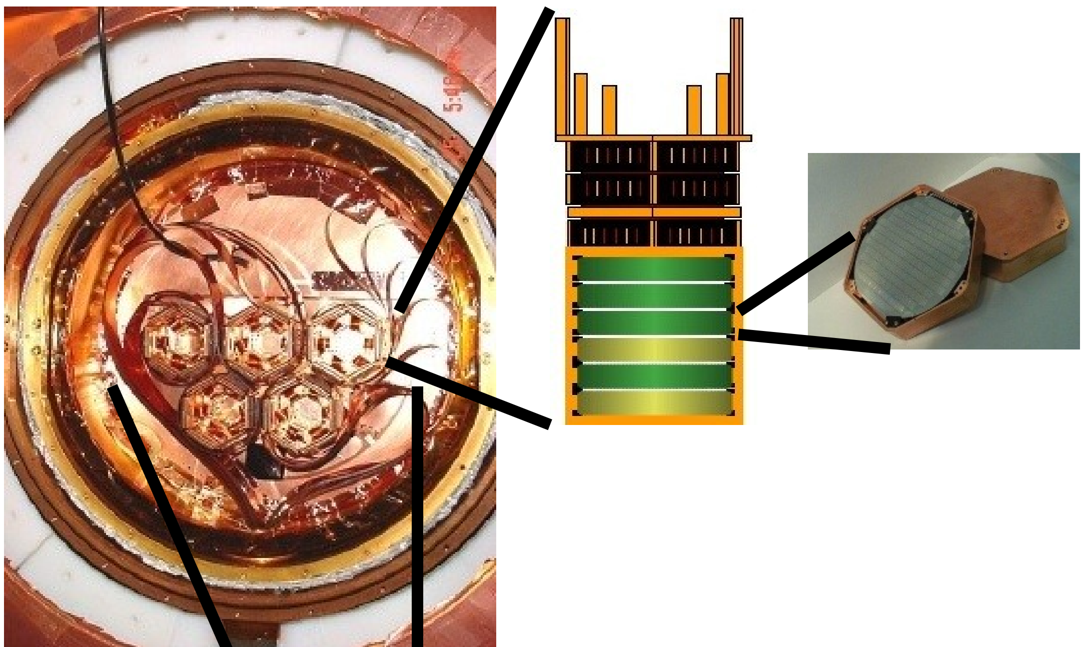
- significant change of the energy spectrum

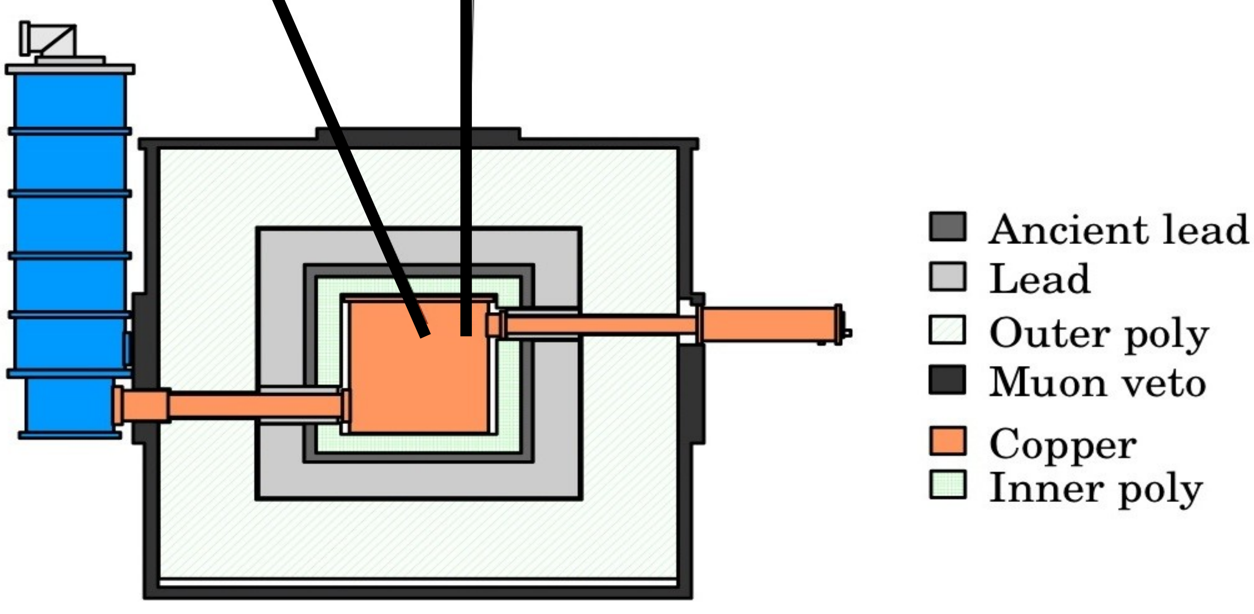
- enhancement of annual modulation



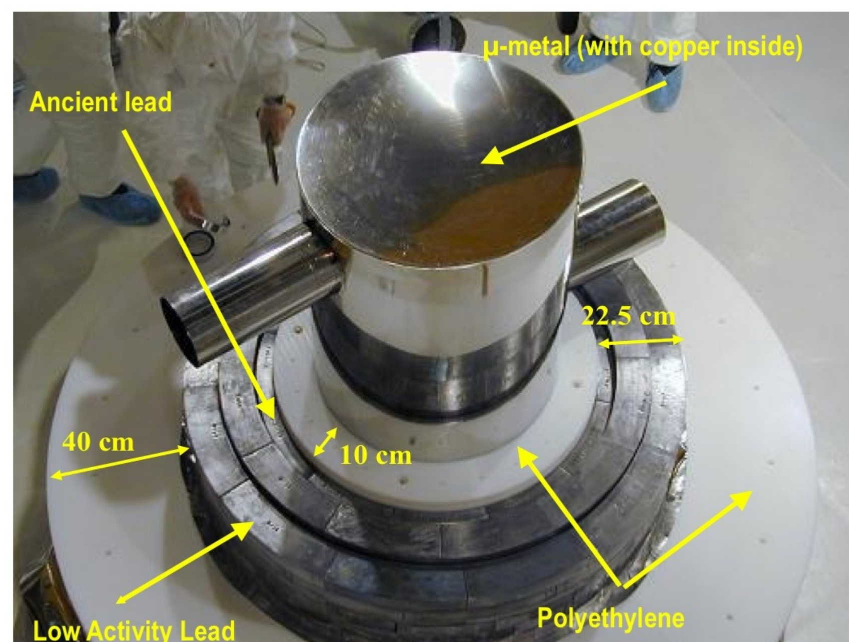
The CDMS Experiment

The CDMS setup & shielding



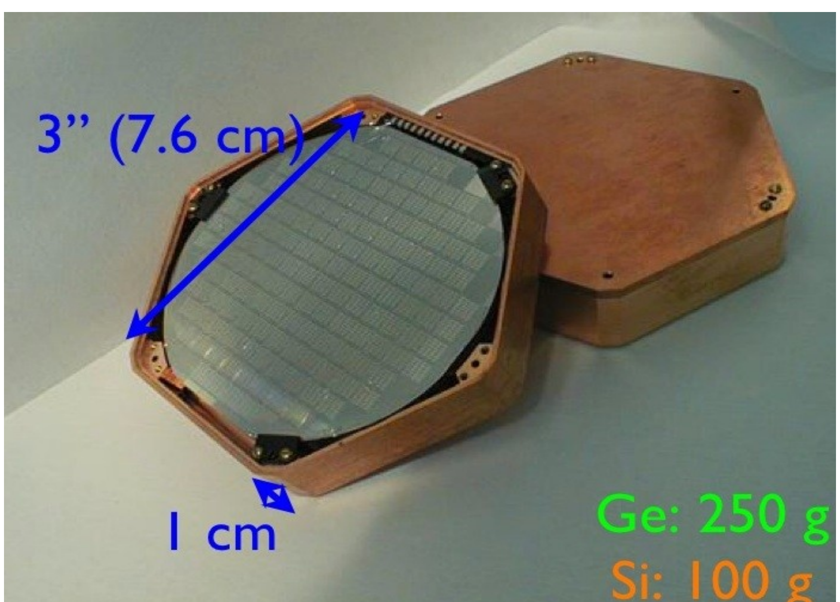


- 5 towers with 6 detectors each
- active veto against high energetic muons
- passive shielding:
  - lead against gammas from radioactive impurities
  - polyethylene to moderate neutrons from fission decays and from (α,n) interactions resulting from U/Th decays

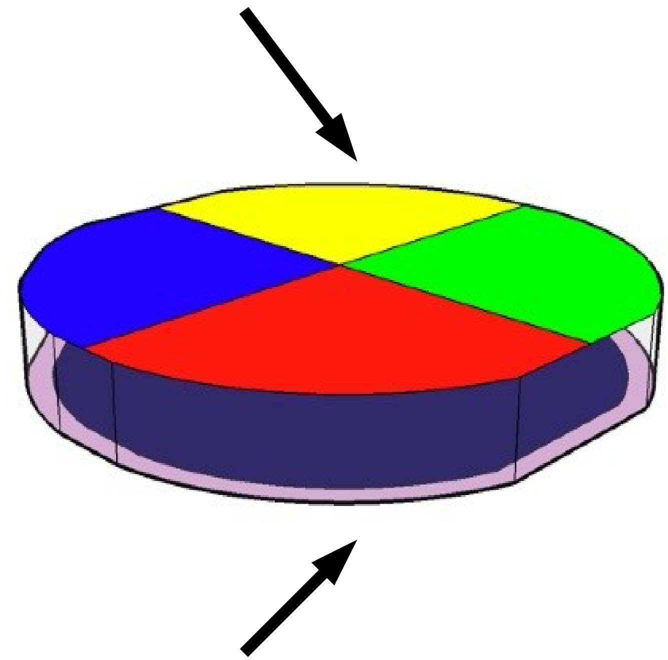


The CDMS ZIP detectors

- 19 Ge and 11 Si semiconductor detectors
- operated at cryogenic temperatures (~40 mK)
- 2 signals from interaction (ionization and phonon) → event by event discrimination between electron recoils and nuclear recoils
- z-sensitive readout
- xy-position imaging



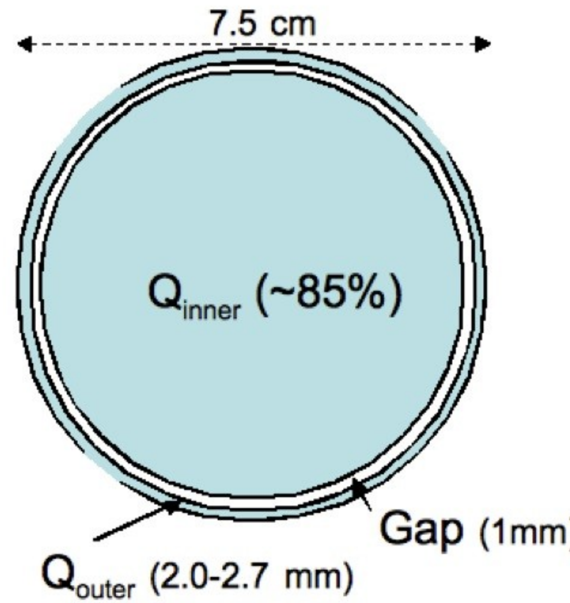
Phonon readout:
4 quadrants of
phonon sensors

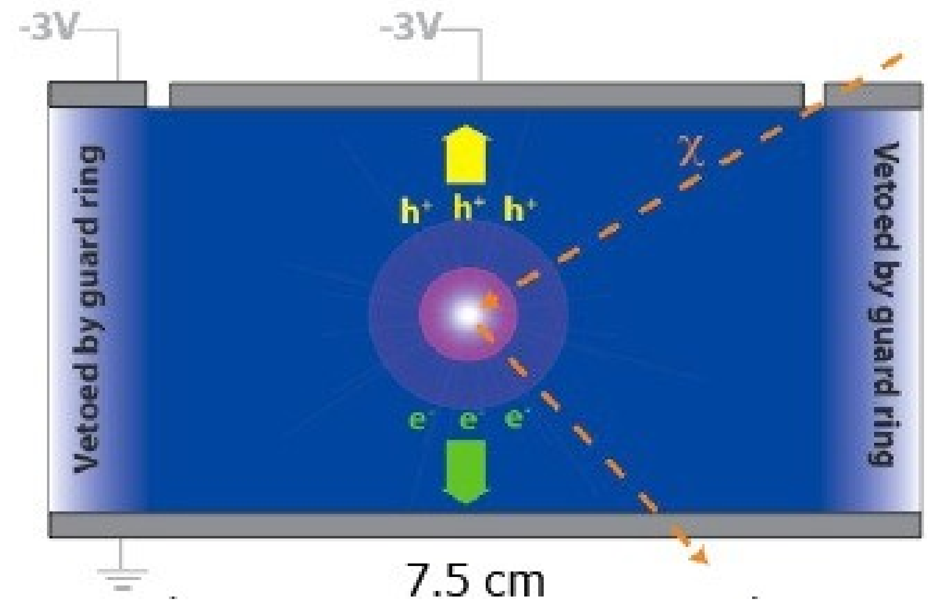


Charge readout:
2 concentric
electrodes

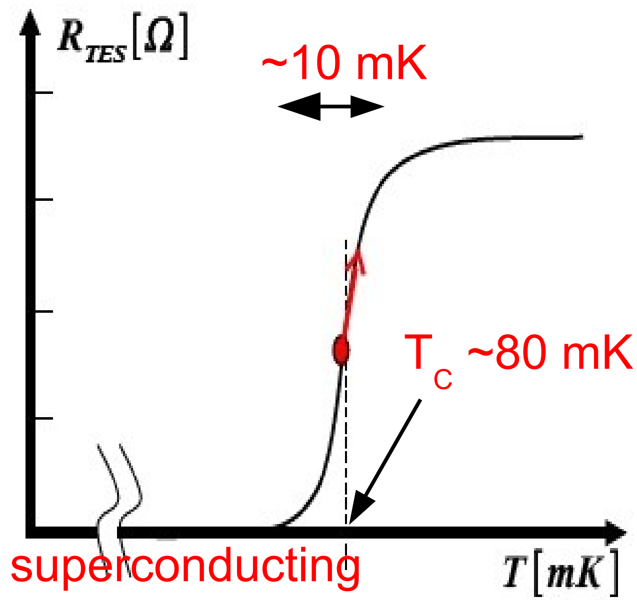
The ionization readout

- interaction creates electron-hole pairs
  → seperate using applied electric field
    → collect charges on electrodes on surface
- drift field of 3 V/cm (4V/cm) on Ge (Si) detectors
- interaction at crystal edges can have incomplete charge collection
  → use outer electrode as guard ring
    → omit Q_{outer} events
- low-energy resolution: 3-4%





The phonon readout

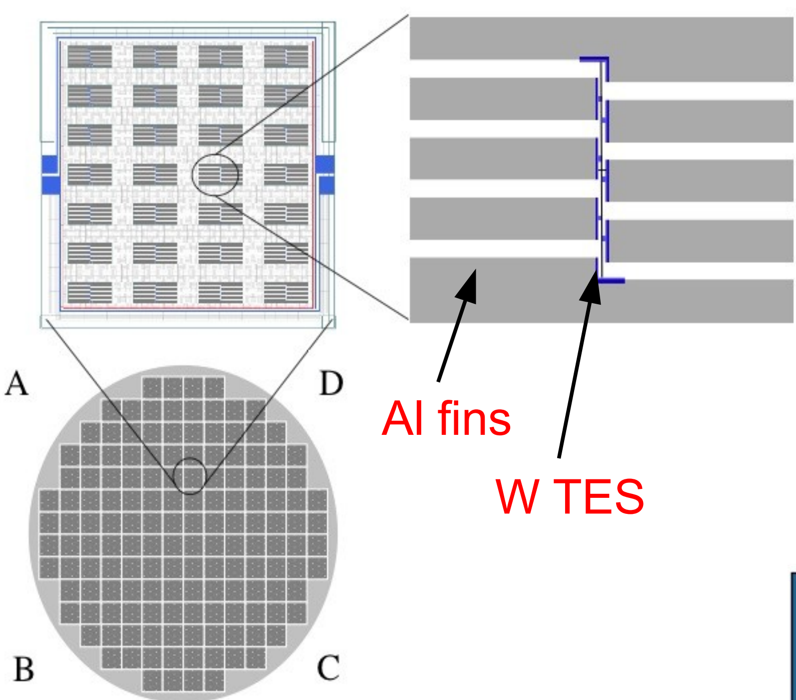


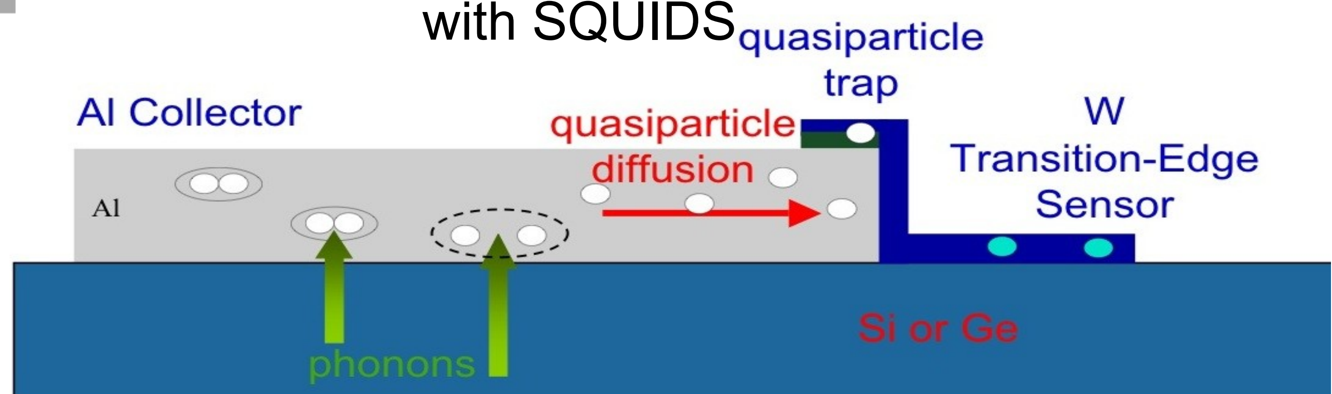
- segmented phonon readout (4 quadrants)
- each quadrant consists of 1036 tungsten TES (Transition Edge Sensors)
- fast response time ~5 μs
- low energy resolution: ~5%
- tungsten strips set just below the edge of superconductivity using bias voltage

→ energy deposition raises temperature

→ conductivity changes to normal

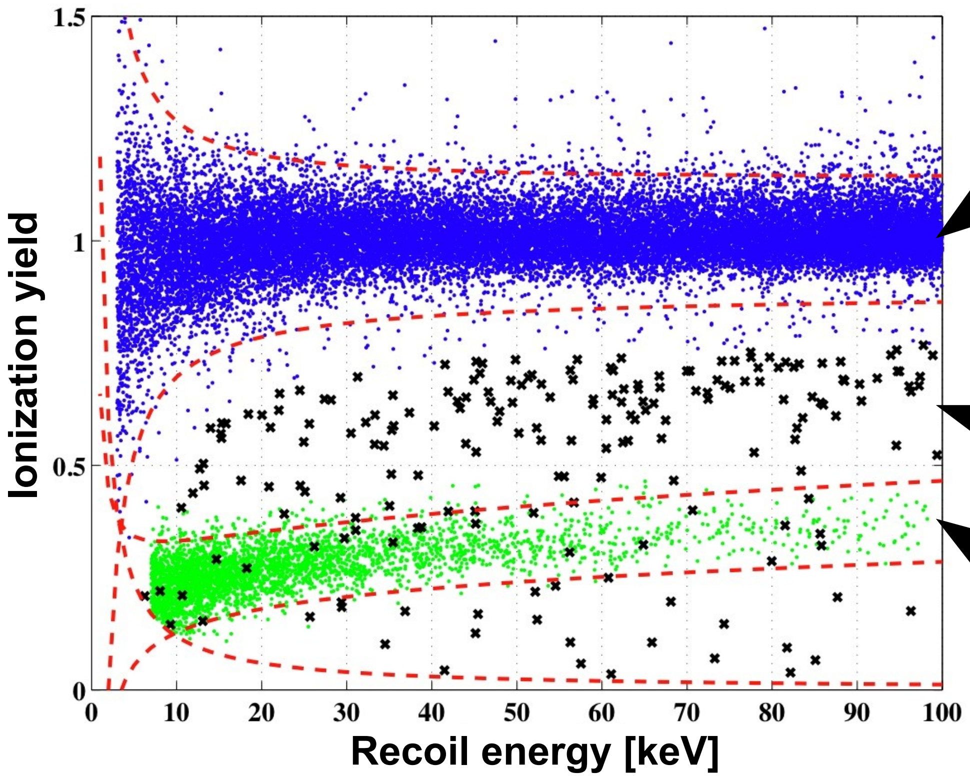
→ dramatic lowering of current read out with SQUIDS

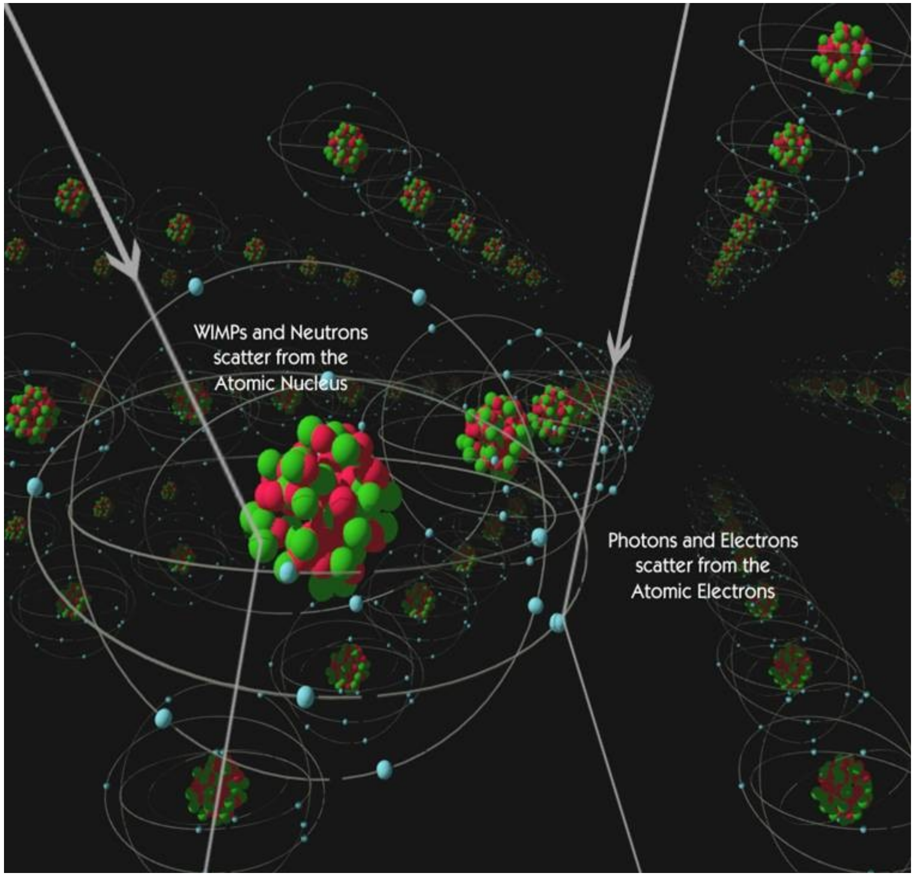




Primary background rejection

- most backgrounds (e, γ) produce electron recoils
- neutrons and WIMPs produce nuclear recoils which have a suppressed ionization signal
- define ionization yield as $y = \frac{E_{charge}}{E_{recoil}}$

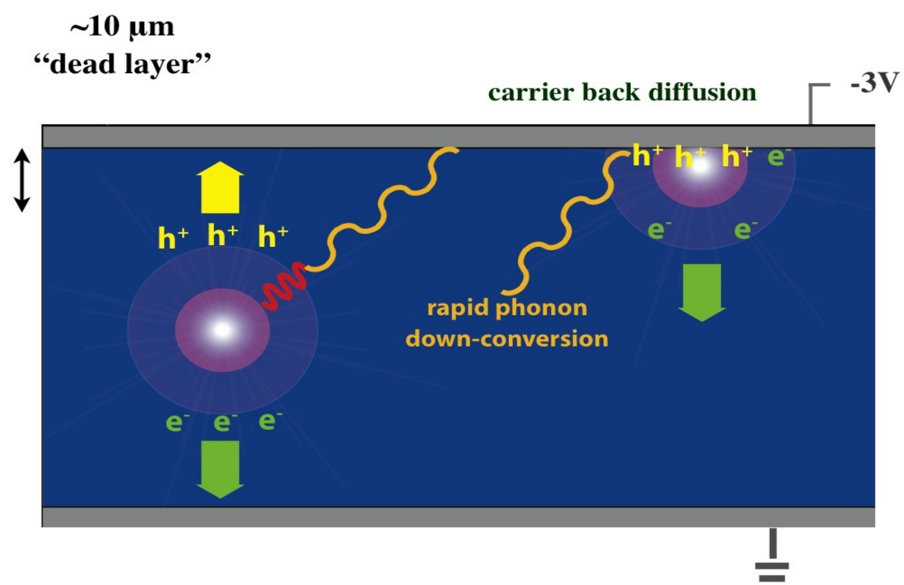




- better than 1:10000 rejection of electron recoils based on ionization yield alone
- dominant remaining background: low-yield surface events

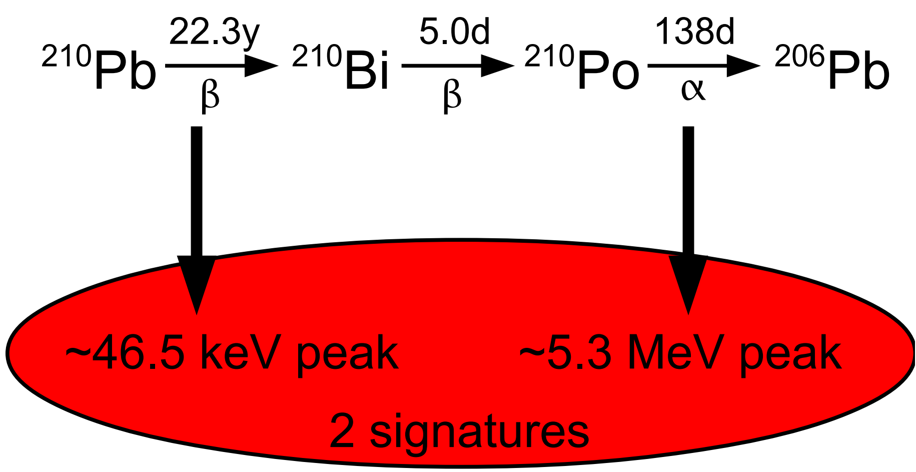
Surface events and contamination

- reduced charge yield due to back-diffusion of charge carriers at the detector surface
- surface event background can be fully accounted for by two sources:
  1. low-energy electrons induced by the ambient photon flux from radioactive impurities in the experimental setup
  2. ^{210}Pb contamination of the detector surfaces



^{210}Pb contamination?

- detetctors are exposed to environmental Radon during fabrication, testing, ...
- ^{210}Pb is a decay product of ^{222}Rn and can be deposited on the detector surfaces
- decay chain:

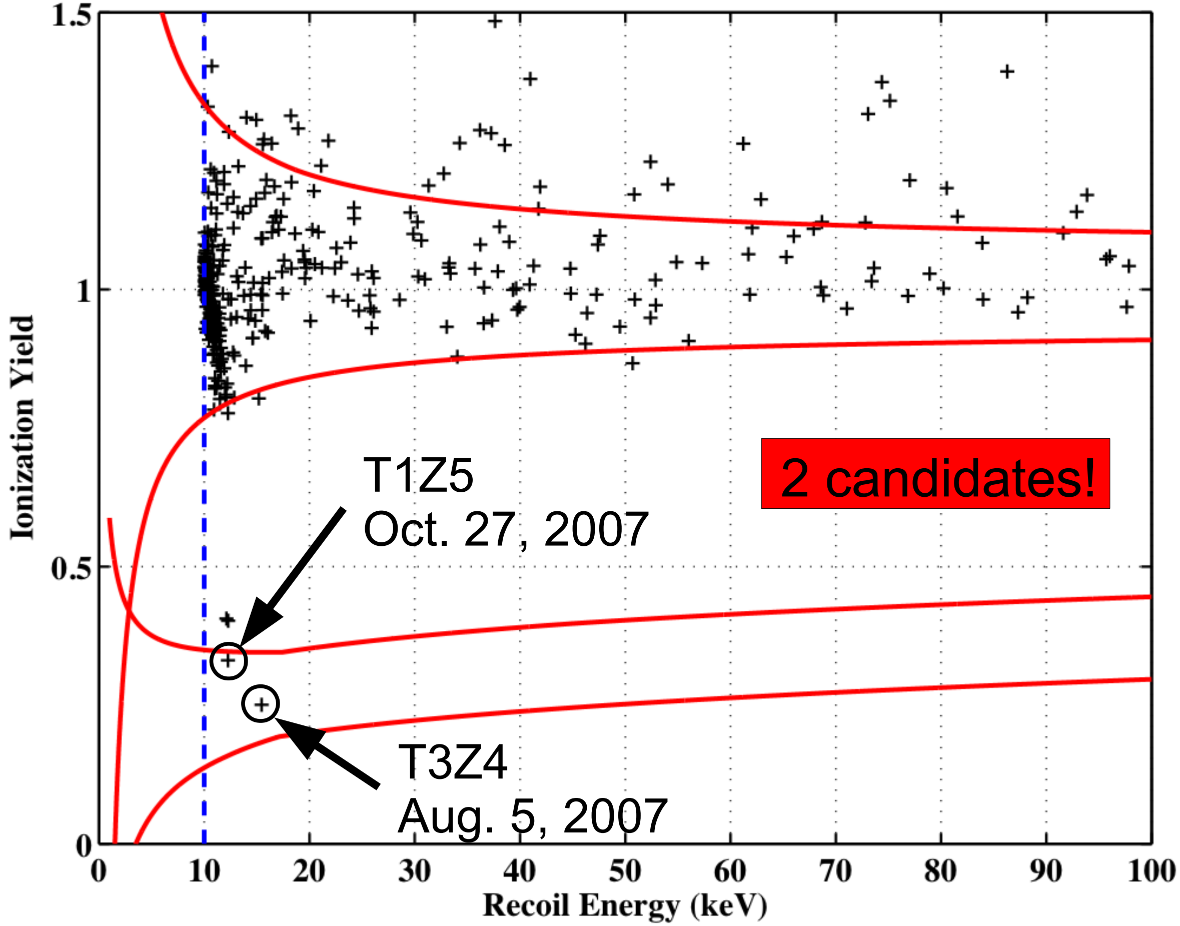


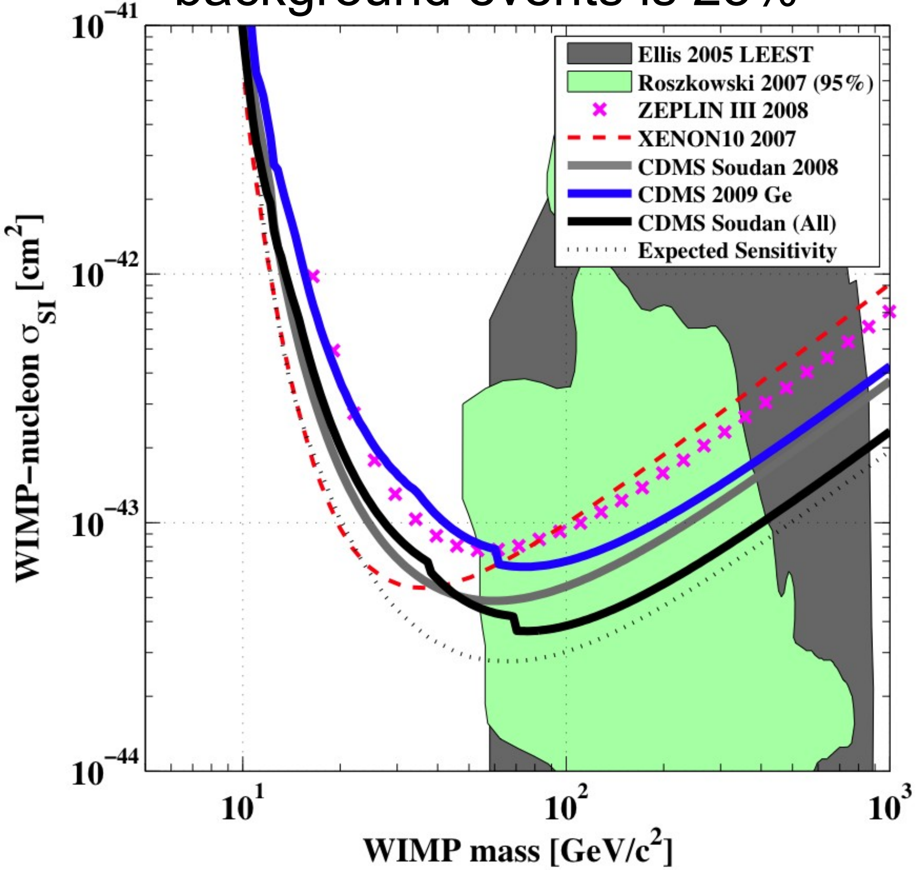
- significant reduction of this contribution for new towers (T3-T5)

CDMS results from the standard analysis

- analysis range: 10 – 100 keV
- two candidate events at 12.3 keV and 15.5 keV

- background of 0.9±0.2 events (predominantly surface events)
- probability for two or more background events is 23%





Science 327, 1619 (2010)

World leading 90% C.L. upper limit on scalar interaction cross sections for WIMP masses above ~70 GeV at time of publication!

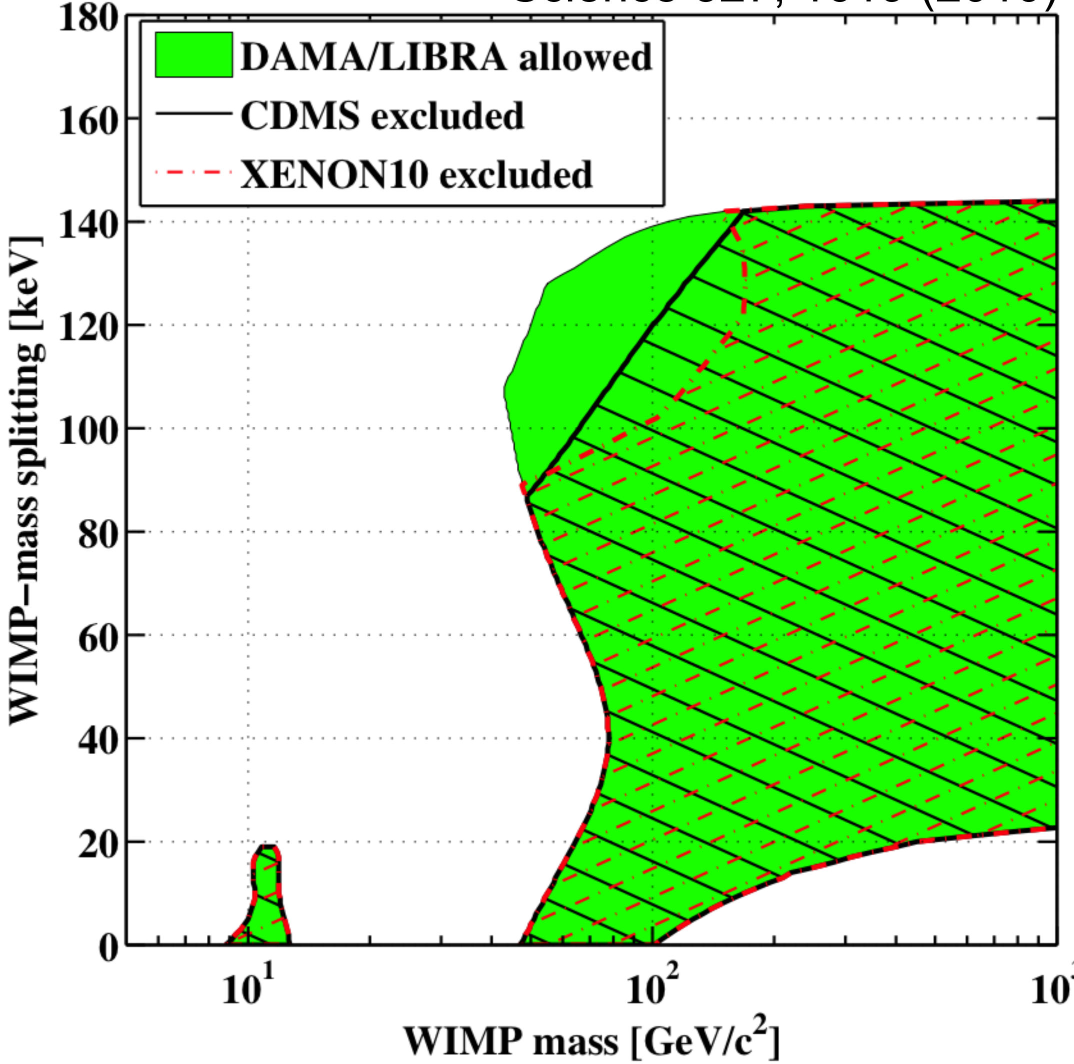
First constraints on IDM from CDMS

- Excluded regions are defined by demanding the upper limit on the cross section to completely rule out the DAMA/LIBRA allowed cross section intervals at a given WIMP mass and mass splitting.

- all limits/allowed regions are @ 90% C.L.

- optimum interval method is used for CDMS and XENON10

Science 327, 1619 (2010)



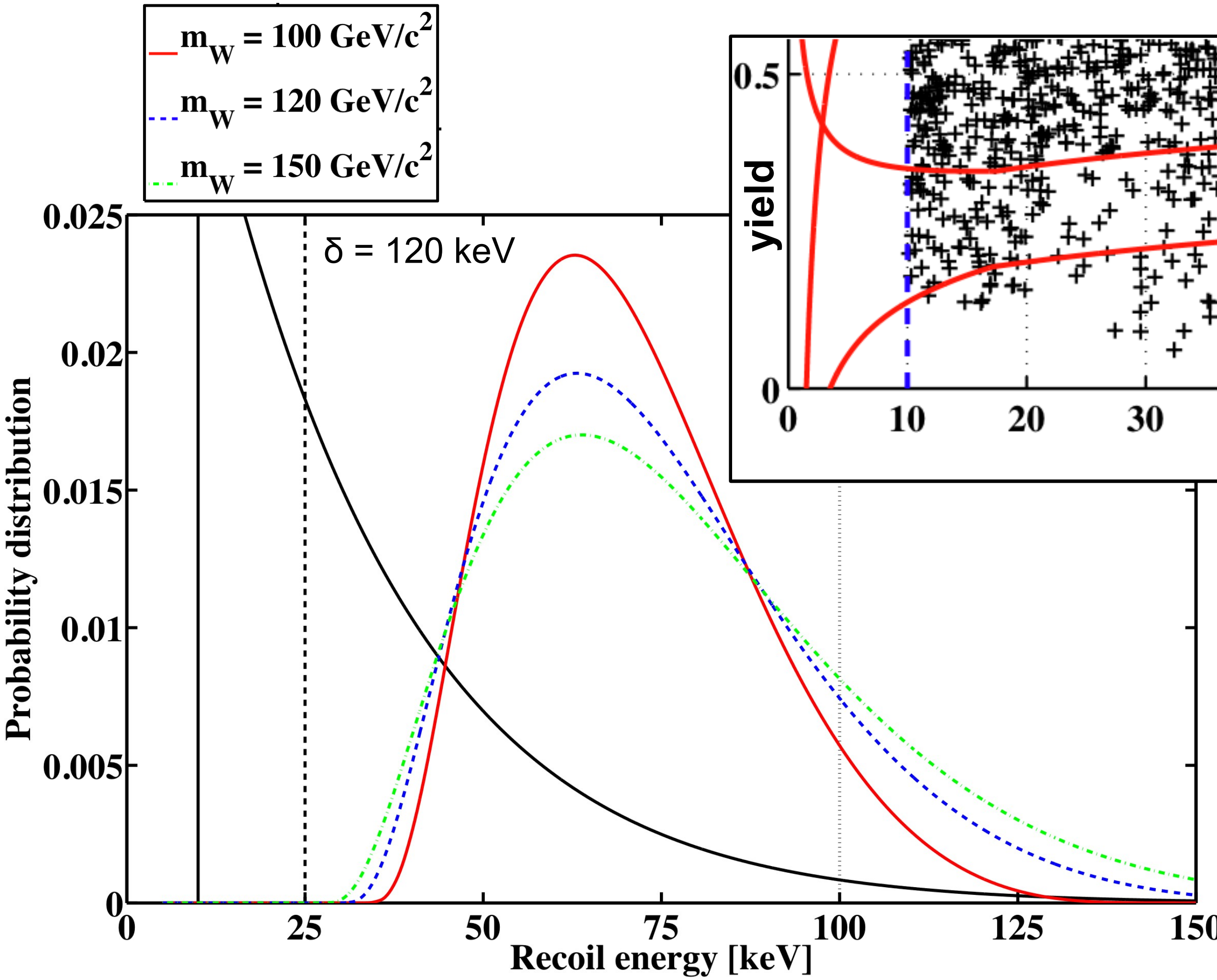
escape velocity: v_{esc} = 544 km/s

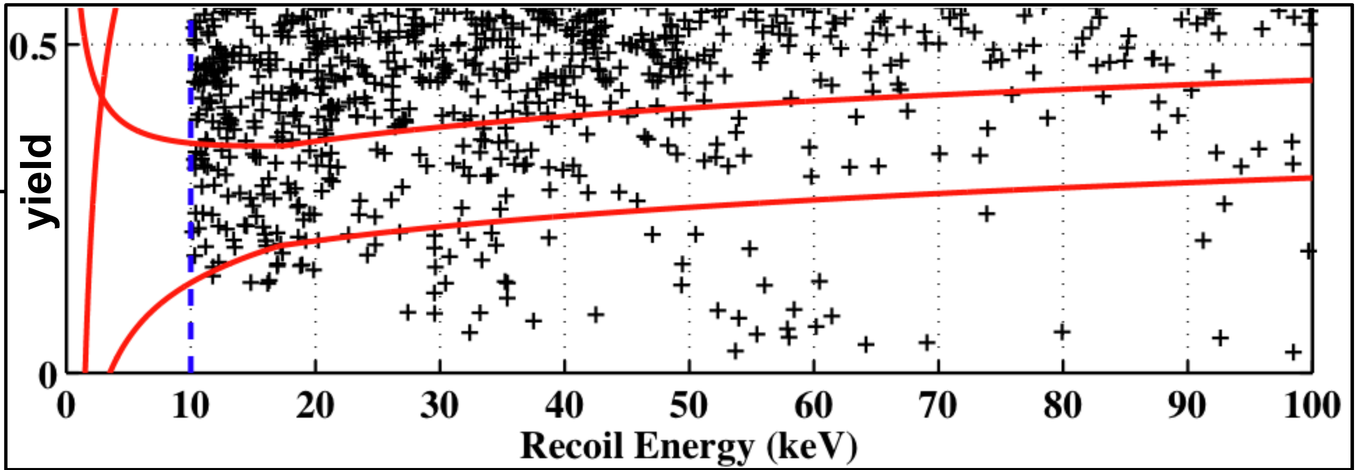
velocity dispersion: v_0 = 220 km/s

DAMA quenching factors: q_I = 0.09 / q_{Na} = 0.30

A dedicated inelastic dark matter analysis

How can we improve the sensitivity?





WIMP search events failing the surface-event rejection cut.

Differential rates in allowed parameter space extend to energies above upper analysis limit (100 keV).

Simply extend analysis range to 150 keV!

Dominant surface event background at low energies where the rate is highly suppressed.

Improve surface event rejection cut!
Use all 6 five tower runs!
Energy range: 25 – 150 keV

Extending the analysis range

- main problem is low statistics in the californium calibration data at energies above ~100 keV

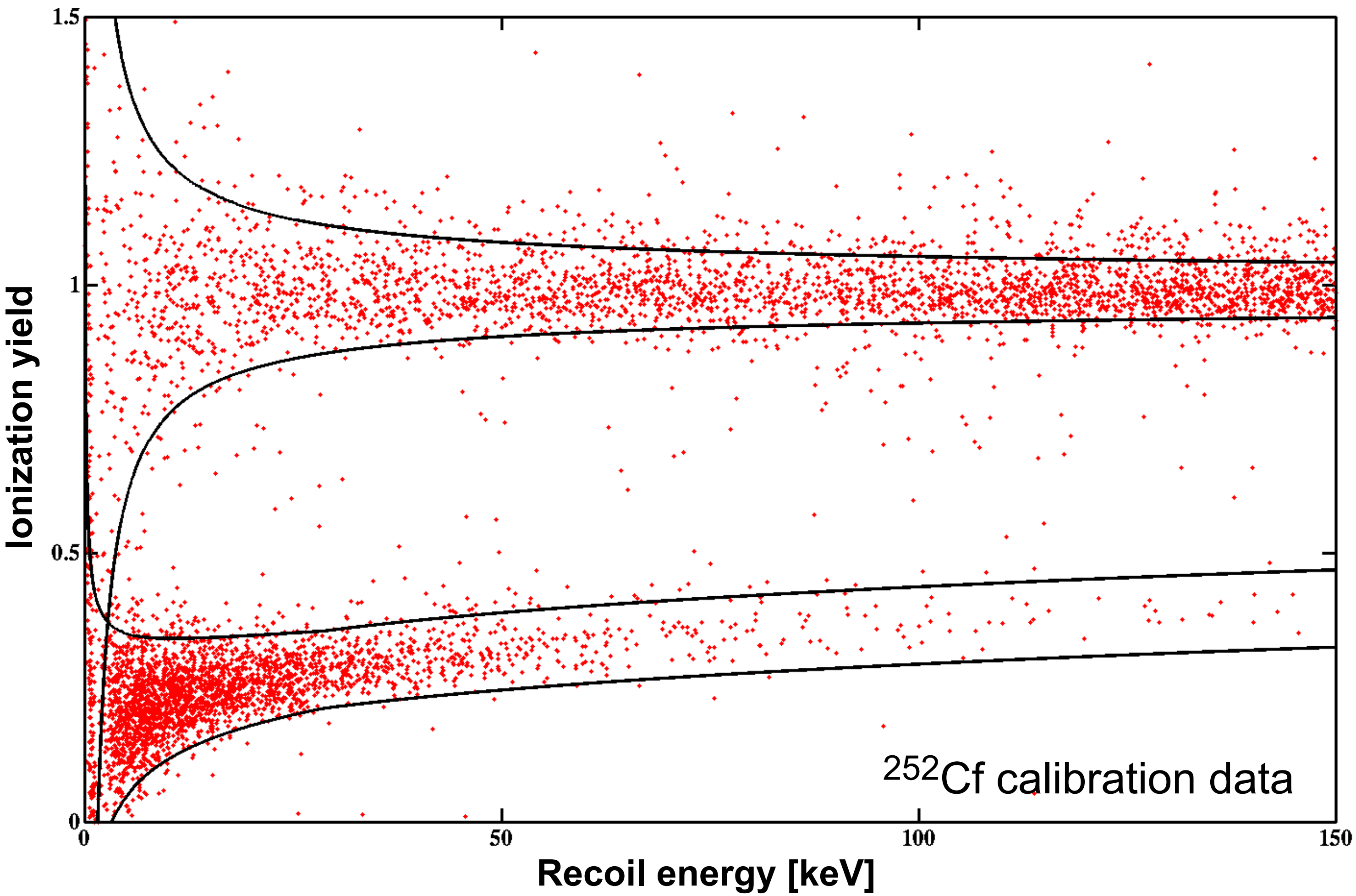
- always check results (cuts/efficiencies) at high energies combining all 6 runs

- compare results from combined data sets with extrapolations from low energies

- be conservative

- No cuts (except surface event rejection) have to be changed.

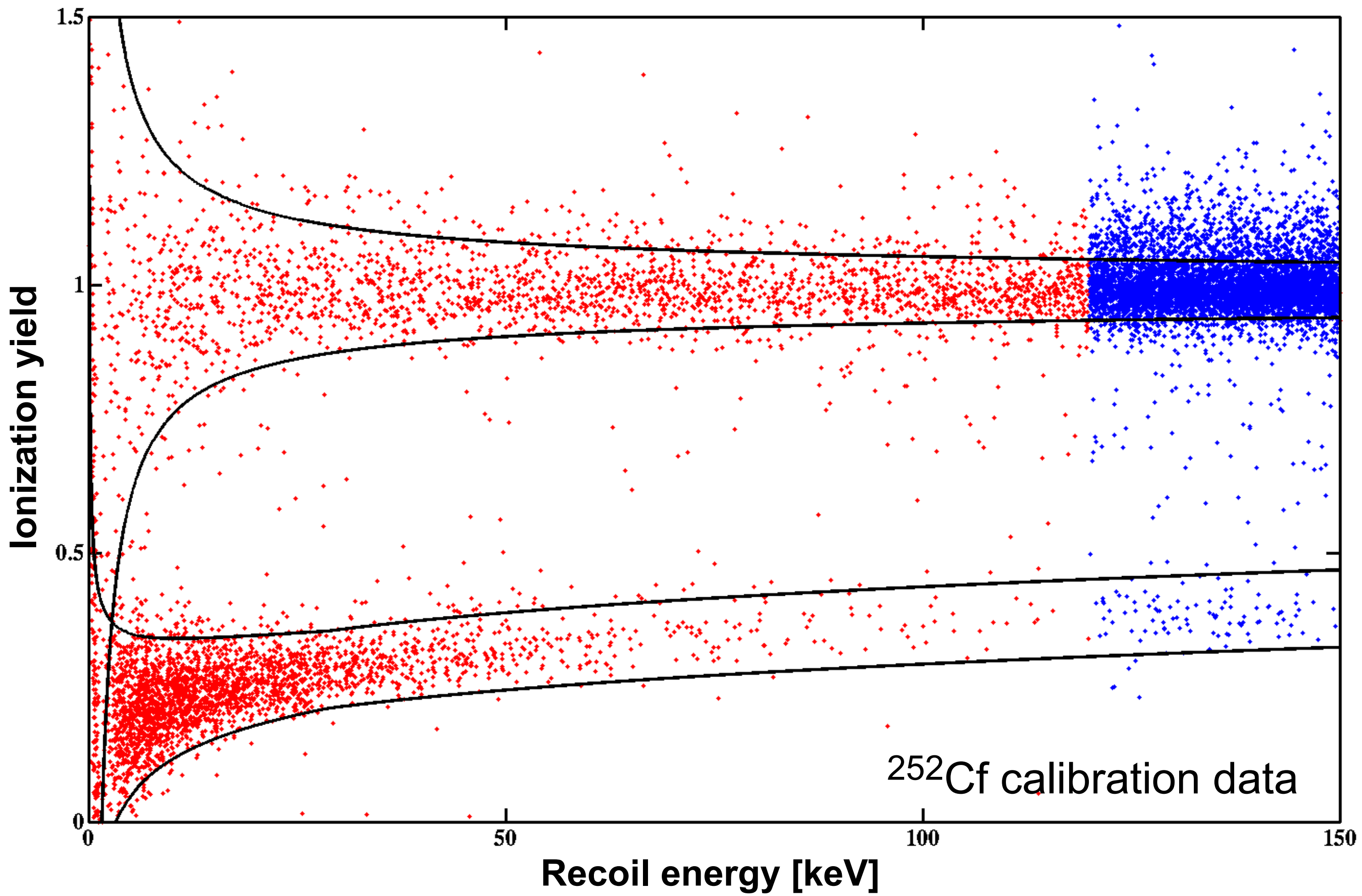
- Possible WIMP candidates above ~100 keV have to be checked with special care!



Extending the analysis range

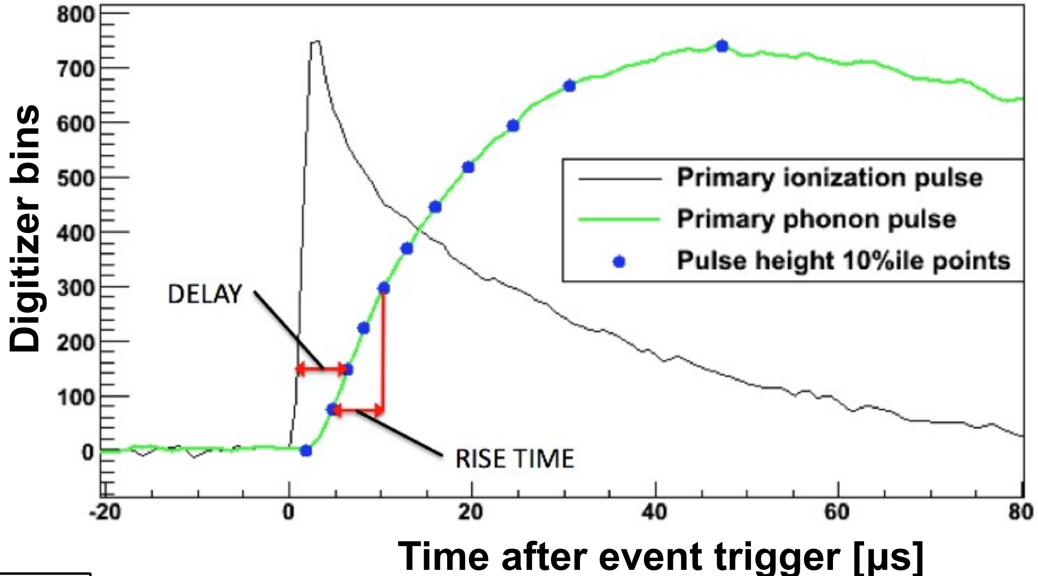
- main problem is low statistics in the californium calibration data at energies above ~100 keV
- always check results (cuts/efficiencies) at high energies combining all 6 runs
- compare results from combined data sets with extrapolations from low energies
- be conservative

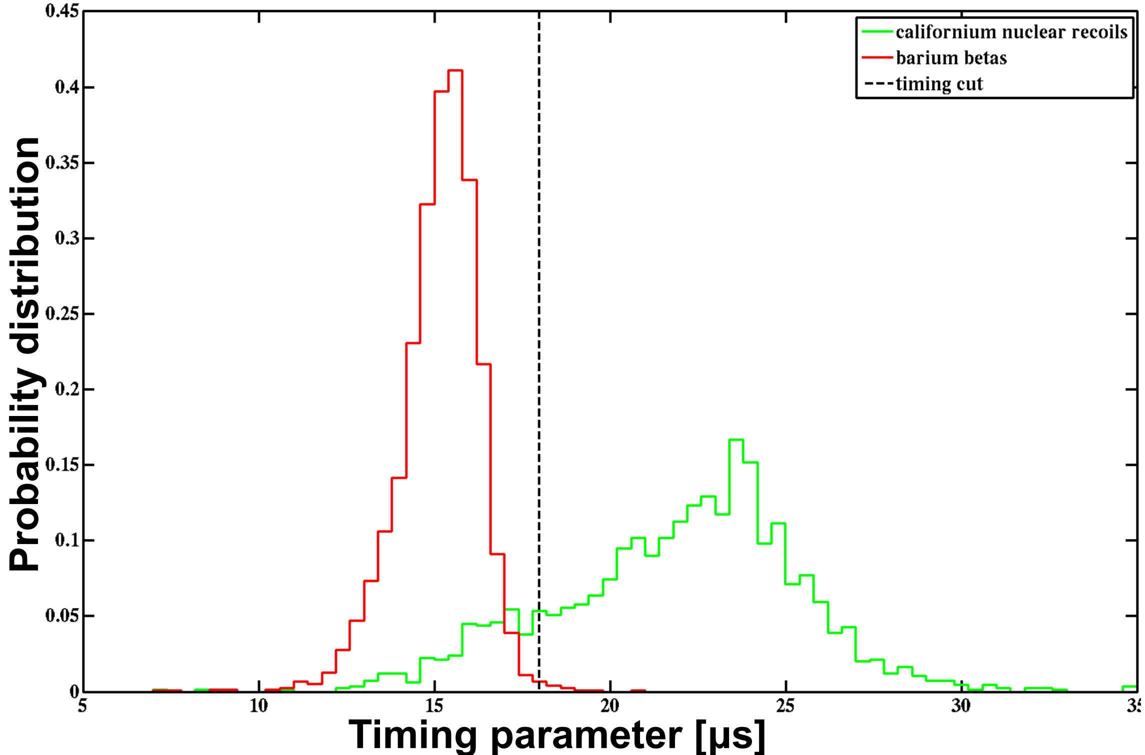
- No cuts (except surface event rejection) have to be changed.
- Possible WIMP candidates above ~100 keV have to be checked with special care!

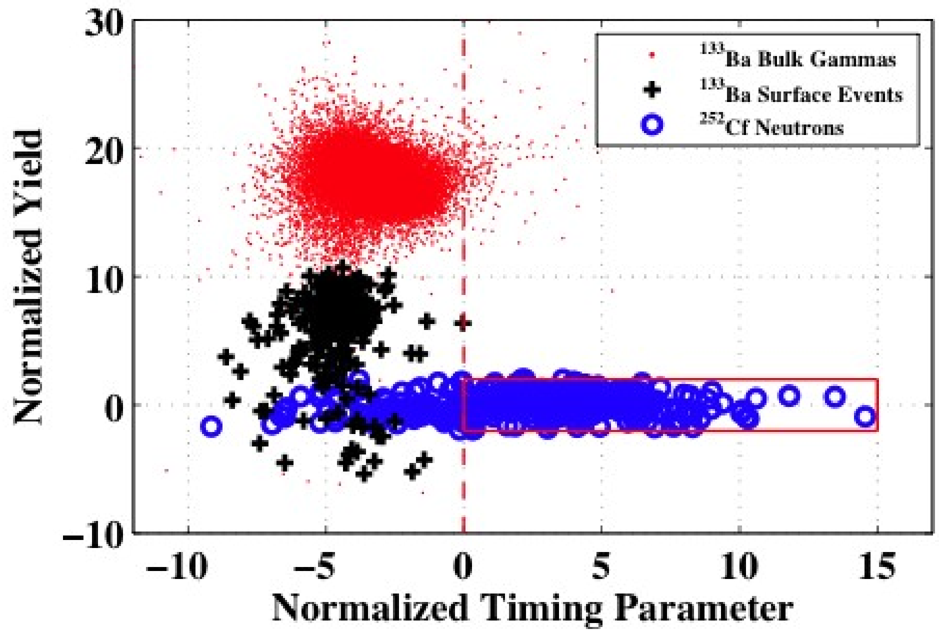


Phonon timing to reject surface events

- Surface events are faster in timing than bulk nuclear recoils.
- Use delay+risetime as discriminator to define cut on calibration data.
- Allow less then one total leakage event in WIMP-search data.







A new surface-event rejection cut

need to use combined 5 tower data
from all 6 runs (969.4 kg-days,
germanium detectors only)

↓

tighter timing cut
for given leakage

↓

lower efficiency

A new surface-event rejection cut

need to use combined 5 tower data from all 6 runs (969.4 kg-days, germanium detectors only)

↓

tighter timing cut for given leakage

↓

lower efficiency

set new timing cut in the energy range of 25-150 keV to evade most of the leakage

↓

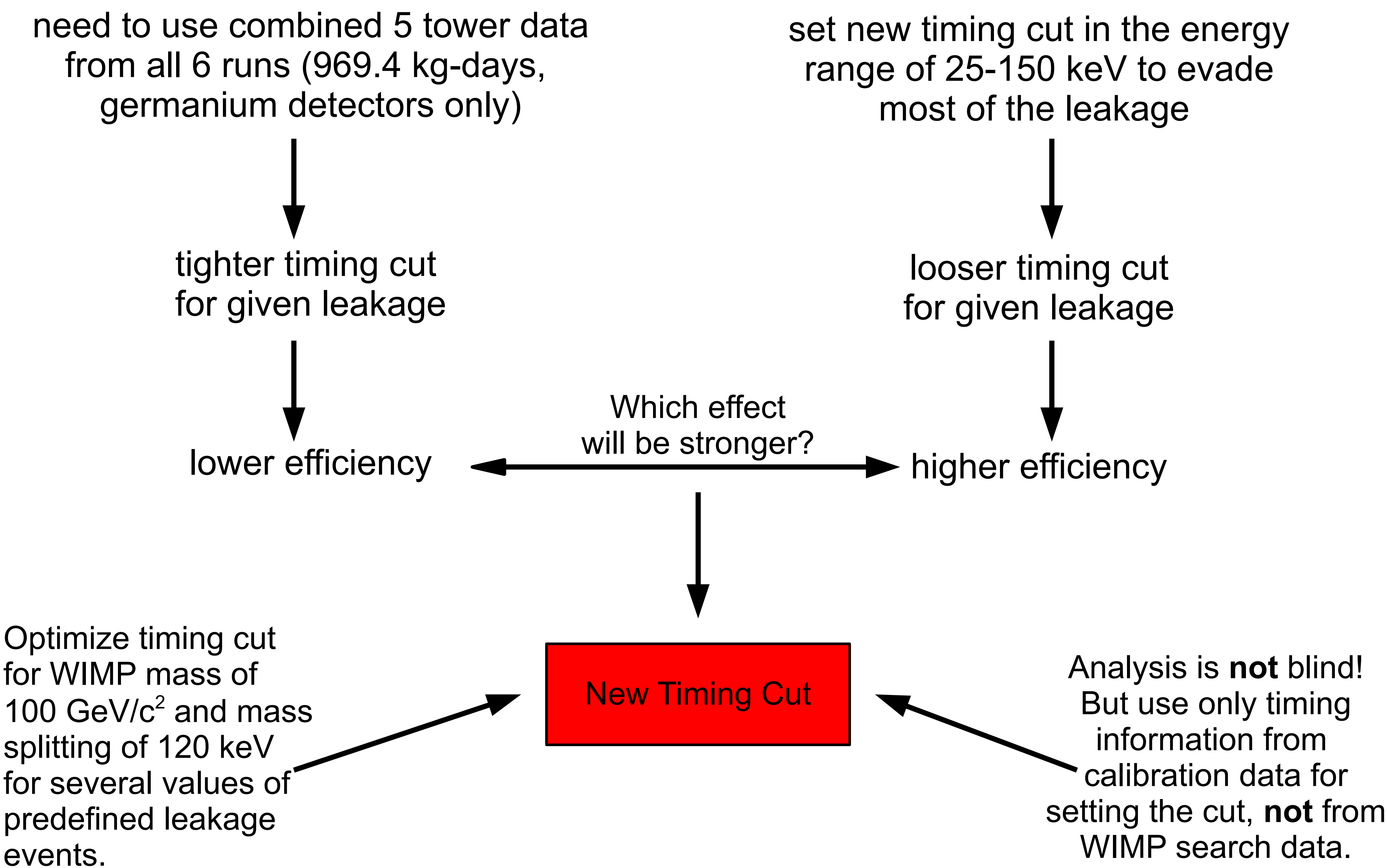
looser timing cut for given leakage

↓

higher efficiency

Which effect will be stronger?

A new surface-event rejection cut

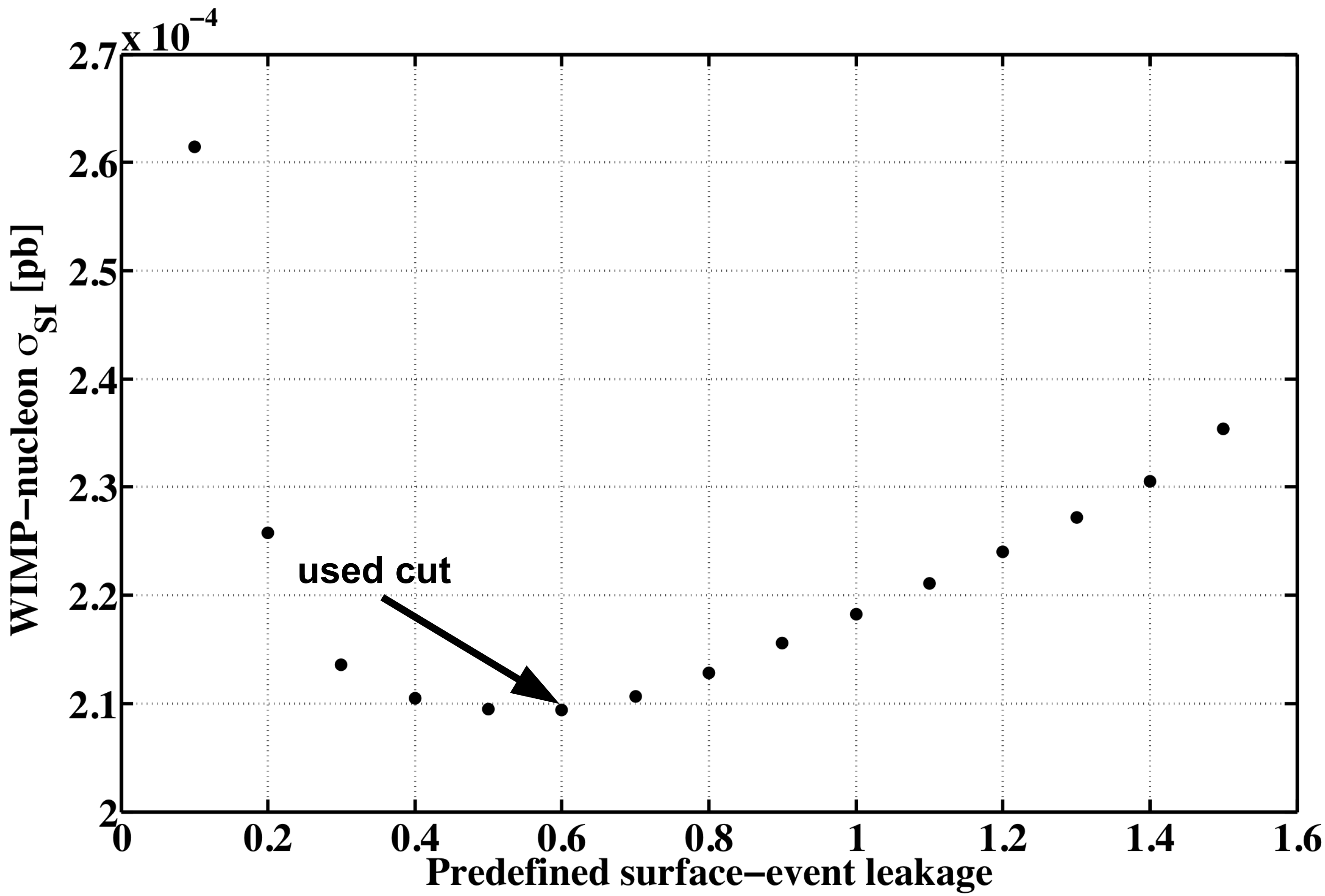


Cut optimization

- calculate sensitivity for cut optimization

- use cut set to 0.6 leakage events (based on calibration data!)

- gain ~20 kg-days exposure (spectrum-averaged exposure) with optimization



Test cut on WIMP-search data.

Surface-event leakage estimate

- expected surface-event leakage: $\mu = \langle N^{fail}_{sing.} \rangle \cdot \frac{\langle N^{pass}_{mult.} \rangle}{\langle N^{fail}_{mult.} \rangle}$

- use two independent event populations for estimating pass/fail-ratios

SIDEBAND 1

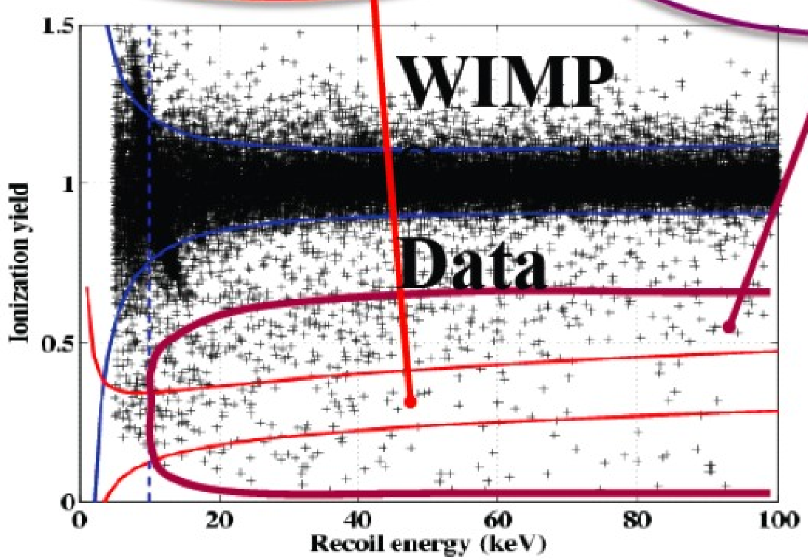
Use multiple-scatters in NR band

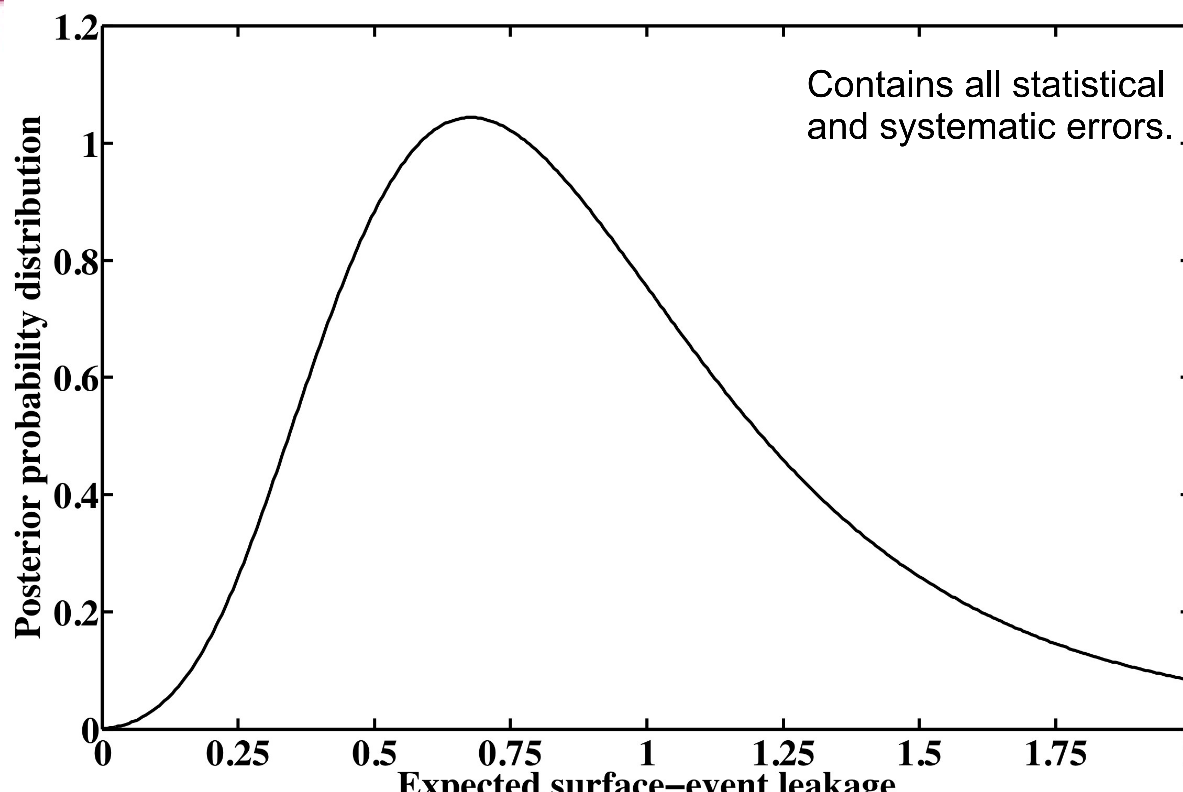
SIDEBAND 2

Use singles and multiples just outside NR band

$0.8^{+0.5}_{-0.3}(\text{stat.})^{+0.3}_{-0.2}(\text{syst.})$

(in 25 -150 keV range, all 6 five-tower runs)





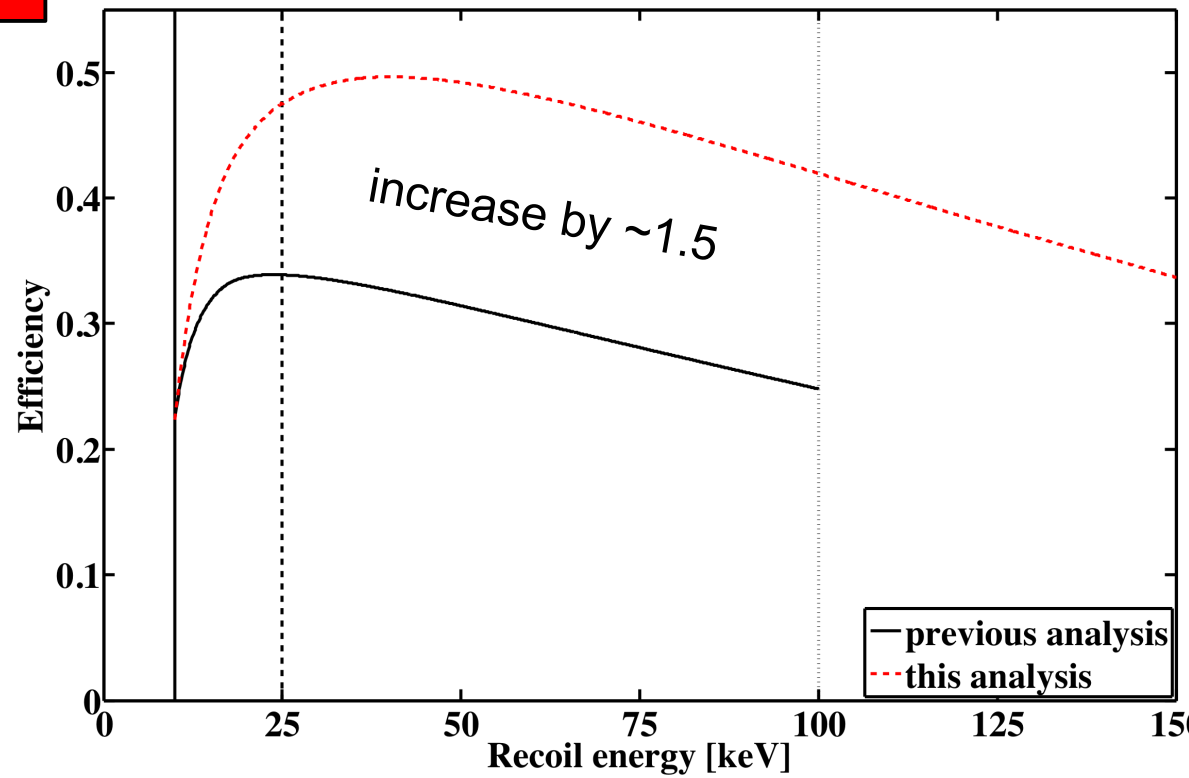
Bayesian approach → treat background as random variable

Analysis summary

“Blind“ Analysis
Set all cuts and calculate efficiencies **before** looking at the signal region of the WIMP-search data.

969.4 kg-days raw exposure

Cut criteria for WIMP candidates:
- energy range: 10 - 150 keV
- data quality
- veto-anticoincidence
- single-scatters
- inside fiducial volume (qinner cut)
- inside 2σ nuclear-recoil band
- no surface event (phonon timing)



Background summary

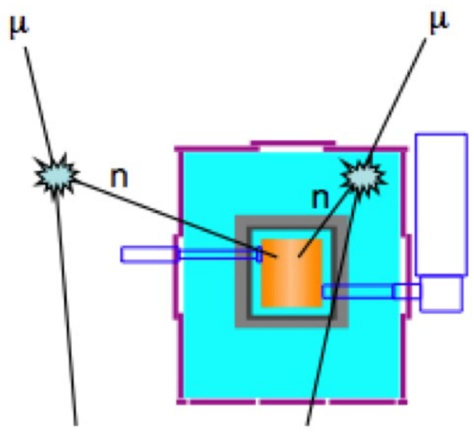
- dominant background: surface events

- neutron background is much less significant

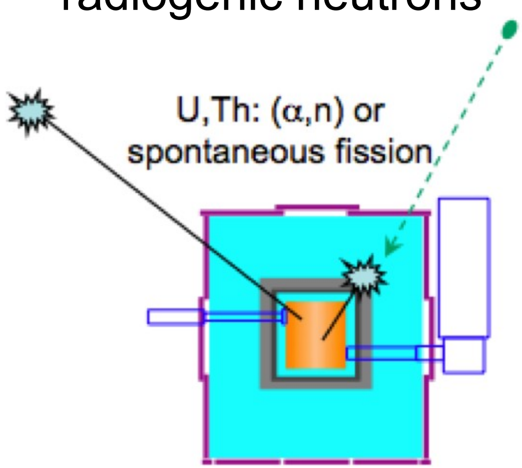
relevant for IDM analysis

	10–25 keV	25–150 keV
Cosmogenic neutron background	$0.06^{+0.07}_{-0.04}$	$0.04^{+0.05}_{-0.03}$
Radiogenic neutron background	0.04–0.08	0.03–0.06
Surface-electron background	$5.7^{+2.1}_{-1.5}$(stat.)$^{+1.0}_{-0.9}$(syst.)	$0.8^{+0.5}_{-0.3}$(stat.)$^{+0.3}_{-0.2}$(syst.)

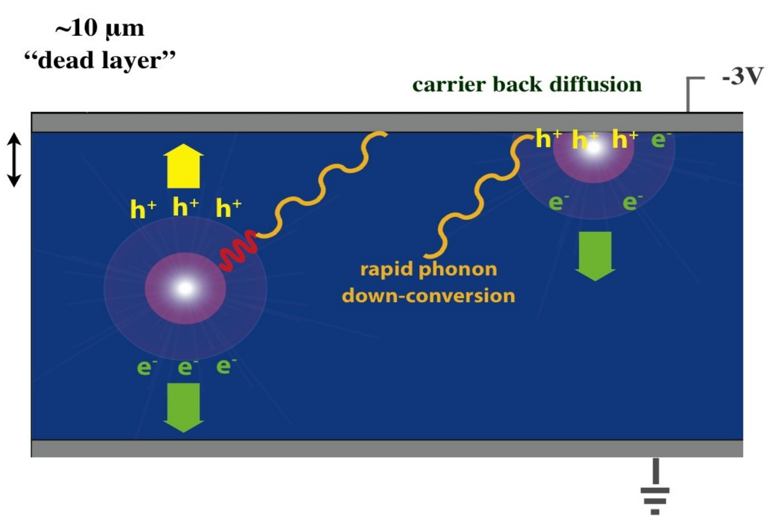
cosmogenic neutrons



radiogenic neutrons



surface events

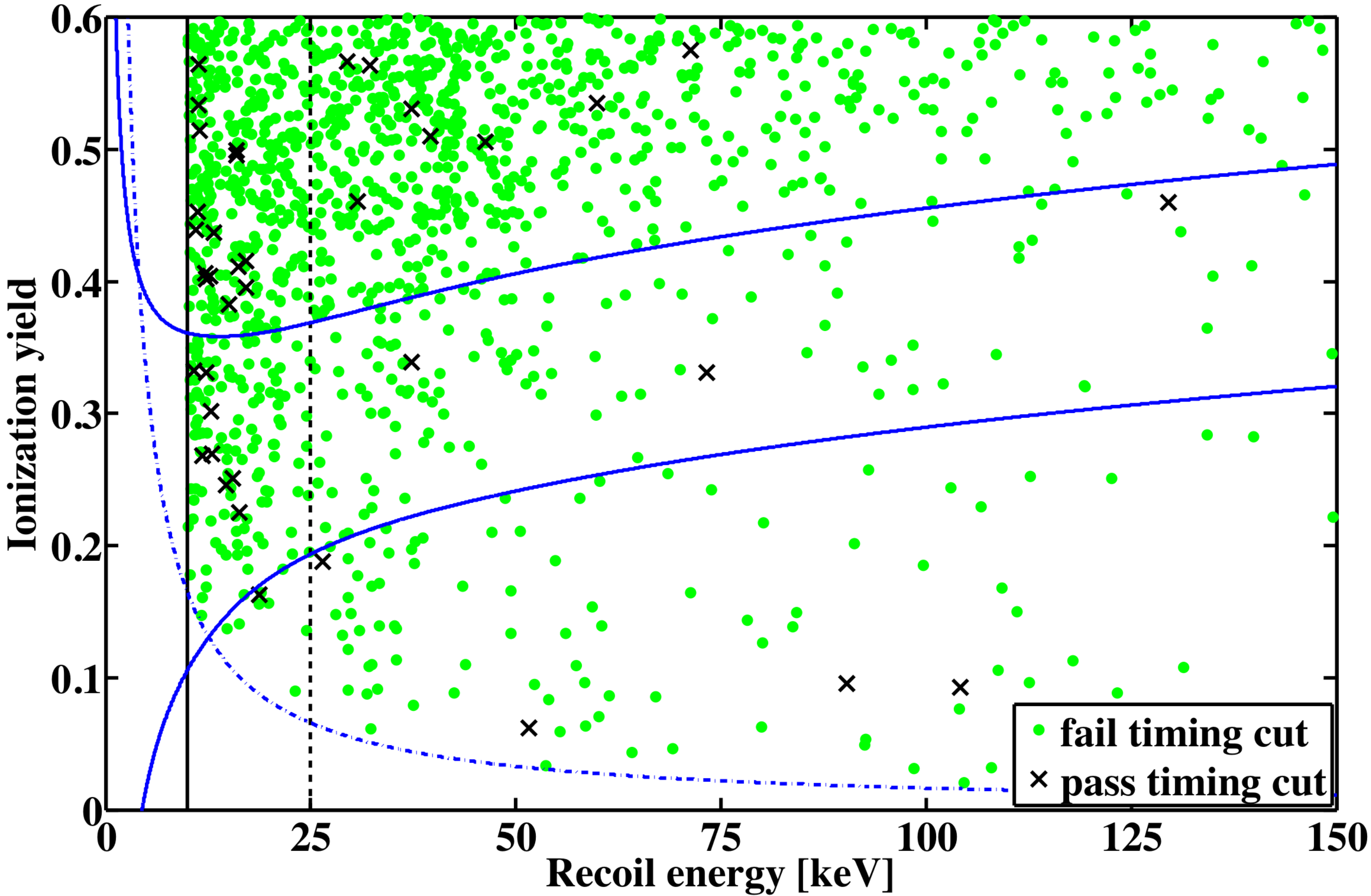


“Unblinding“

10 – 25 keV: 8 events (29% probability for 8 or more background events)

25 – 150 keV: 3 events (11% probability for 3 or more background events)

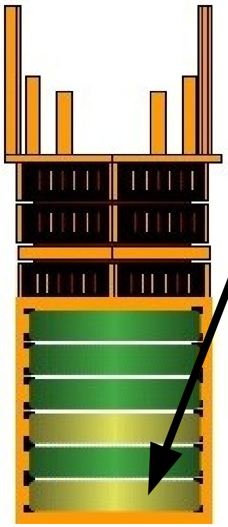
$$p(\geq N_{\mathrm{obs}}\ \mathrm{events}) = \int_0^\infty \mathrm{d}\mu\ P(\mu) \cdot \sum_{k=N_{\mathrm{obs}}}^{\infty} \frac{\mu^k e^{-\mu}}{k!}$$

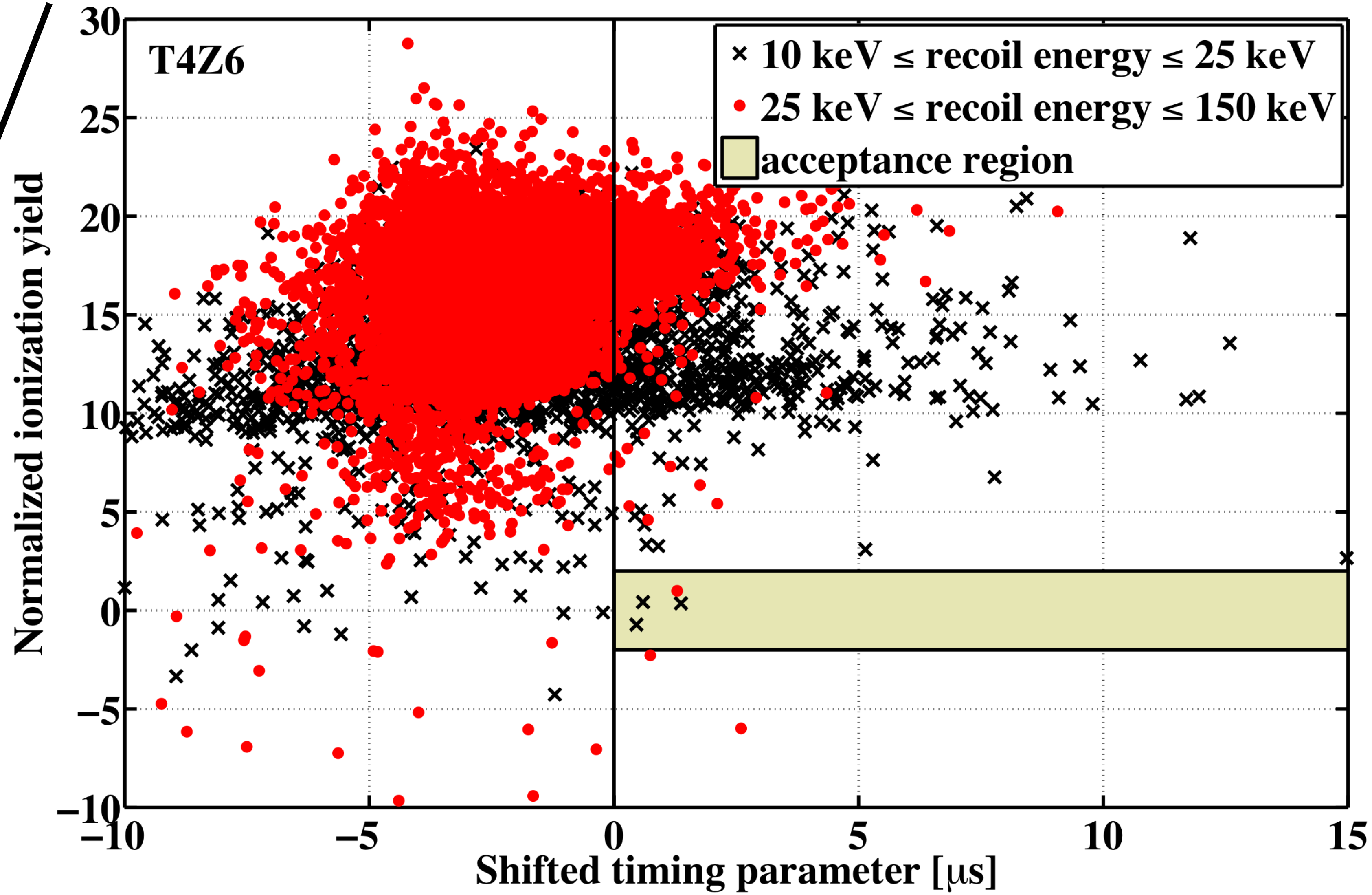


“High-energy“ event 1

T4Z6 @ 37.3 keV Feb. 2, 2008

Endcap detector!

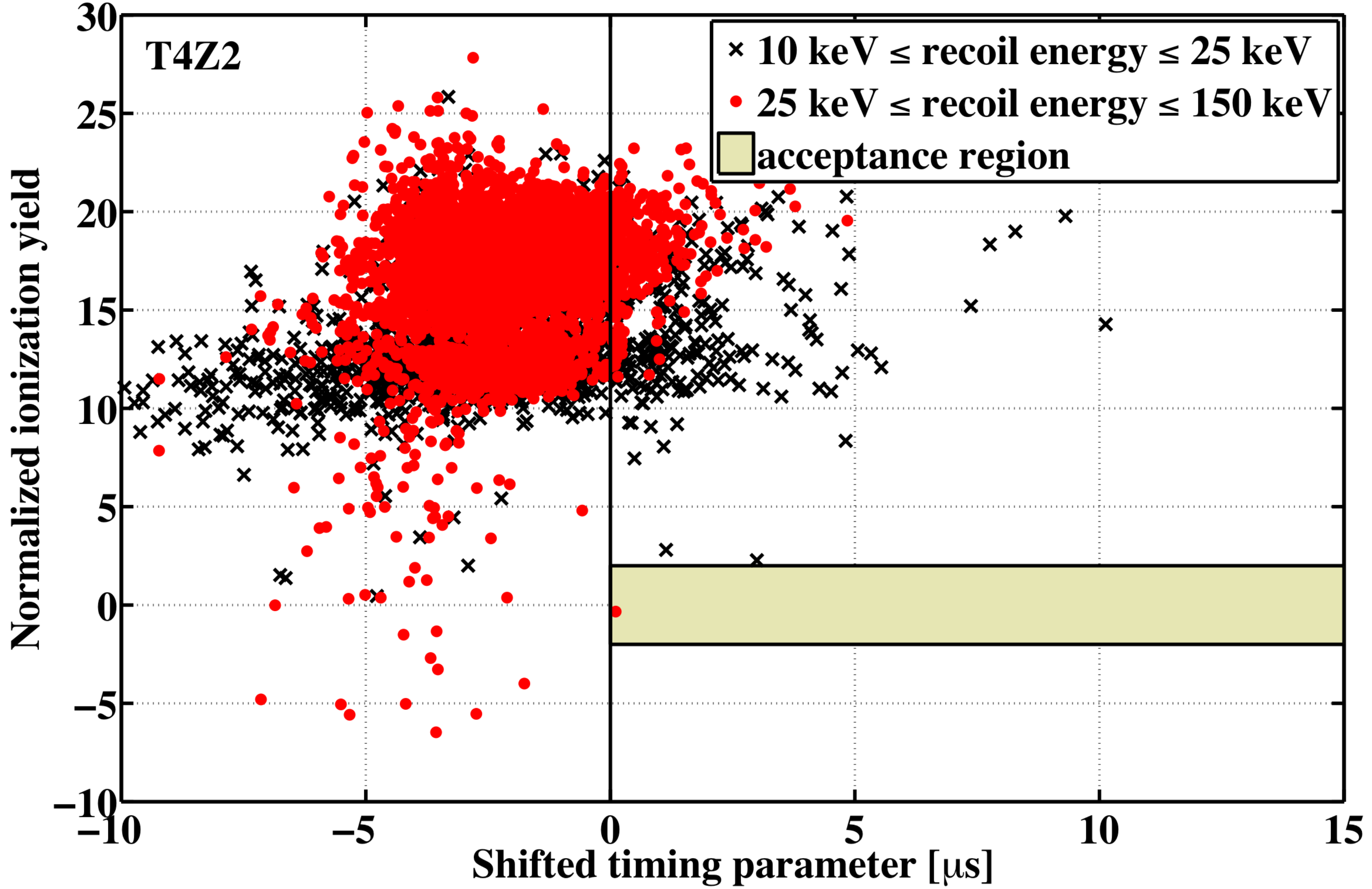




“High-energy“ event 2

T4Z2 @ 73.3 keV Feb. 4, 2008

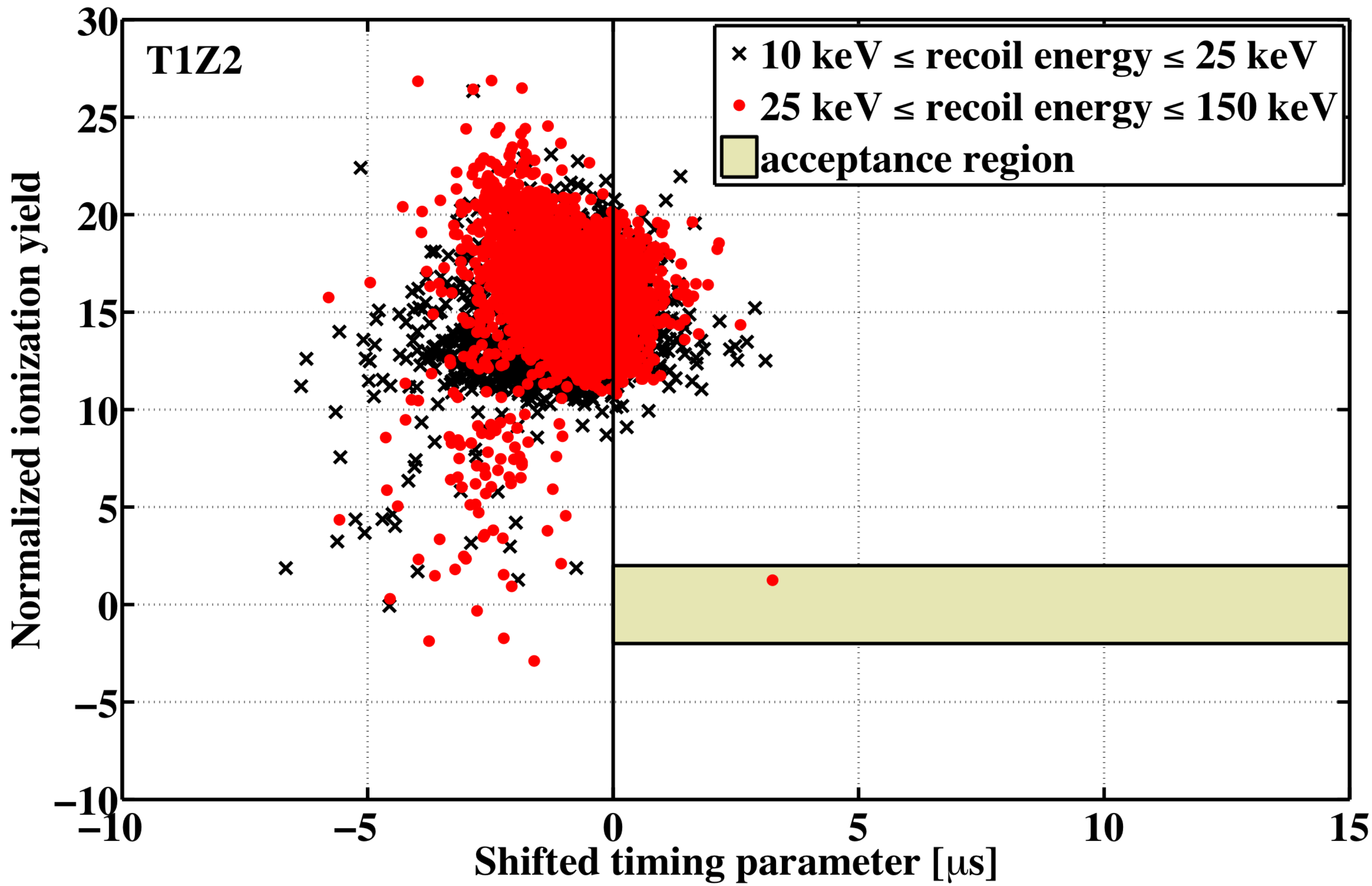
Extremely close to timing cut boundary!



“High-energy“ event 3

T1Z2 @ 129.5 keV Christmas Eve, 2006

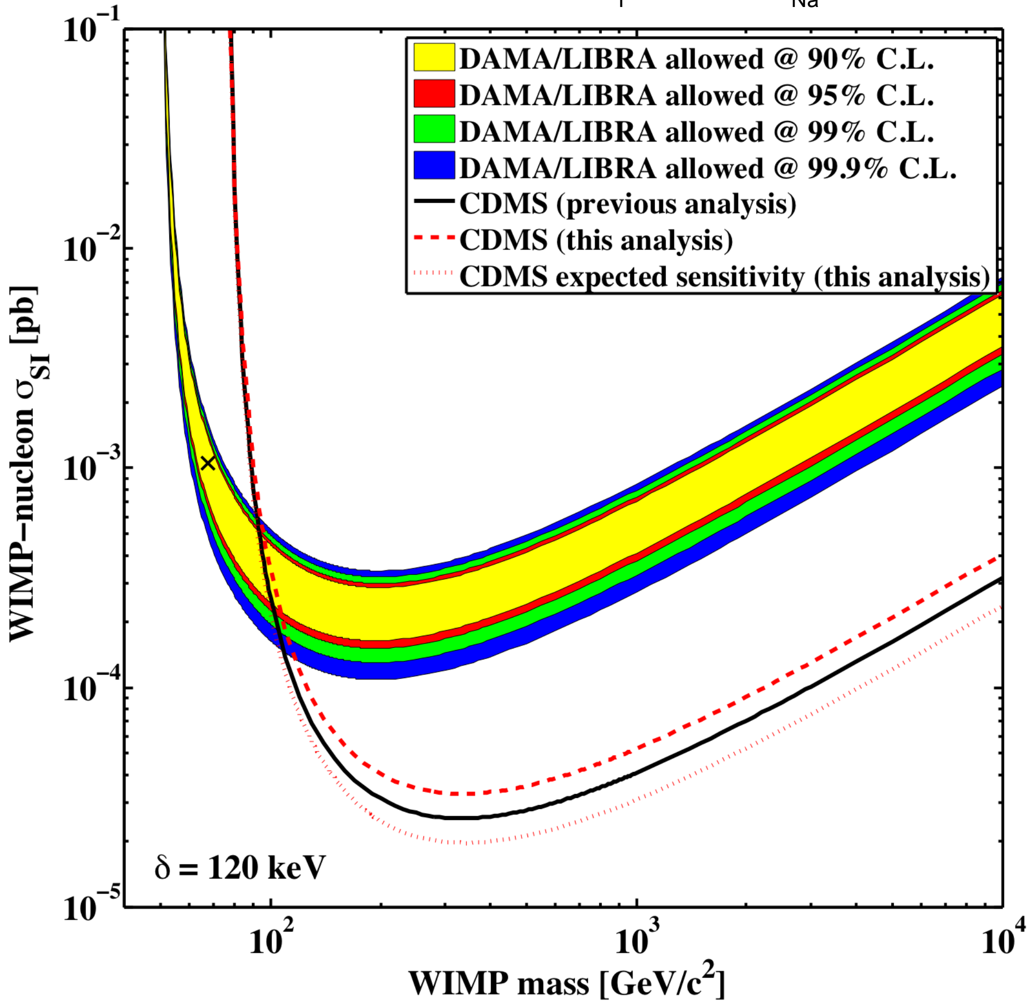
Not even cut by timing cut set to 0.1 leakage events / cut from previous analysis!



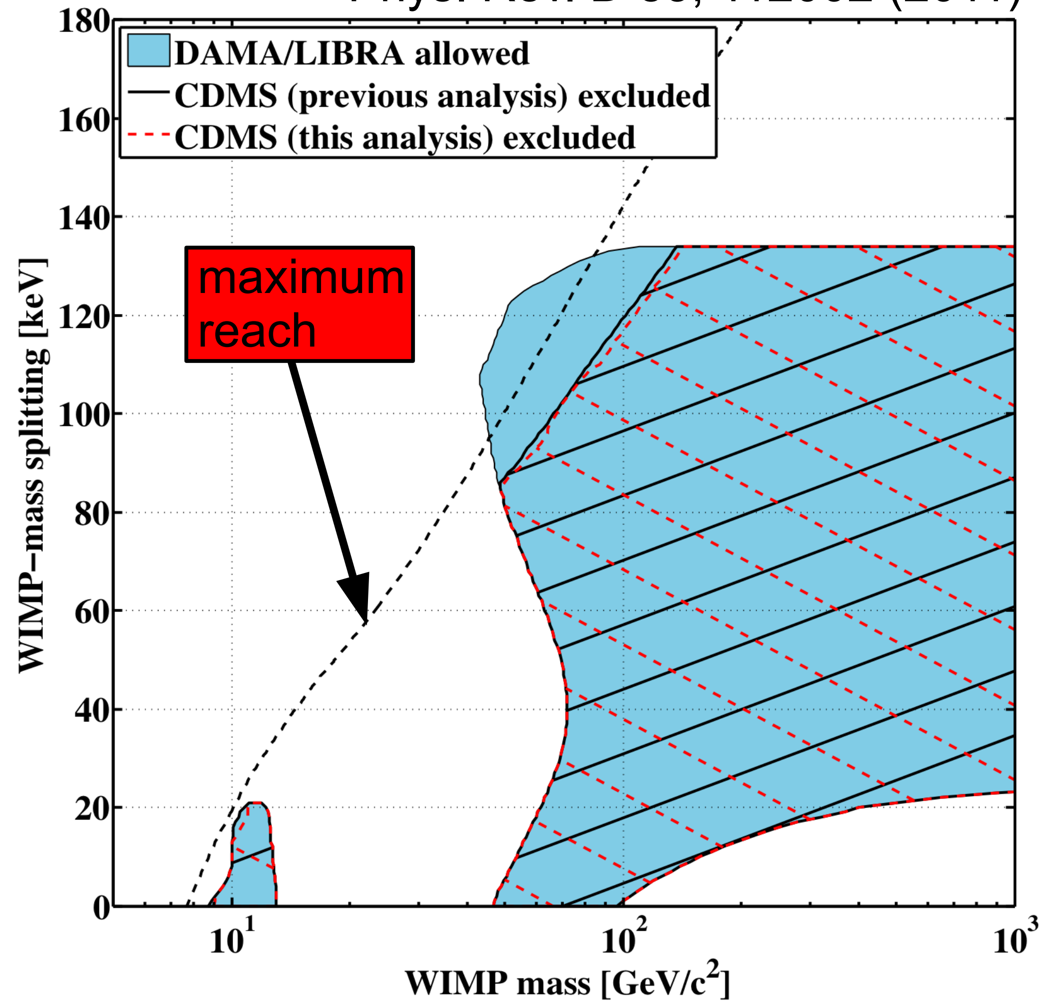
Constraining the IDM model

Due to the occurance of the three "high-energy" events the limit is weaker.

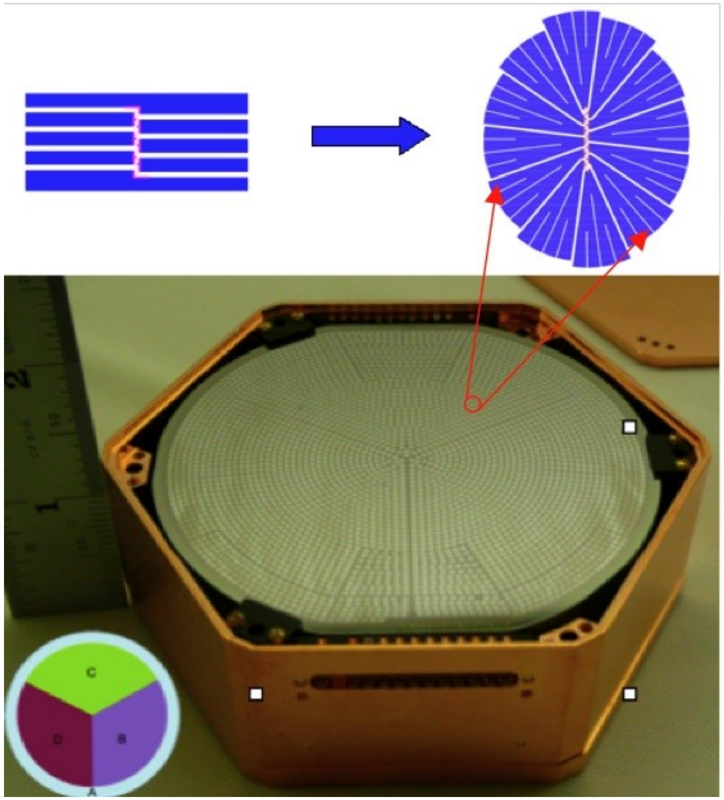
escape velocity: v_{esc} = 544 km/s
velocity dispersion: v_0 = 220 km/s
DAMA quenching factors: q_I = 0.09 / q_{Na} = 0.30



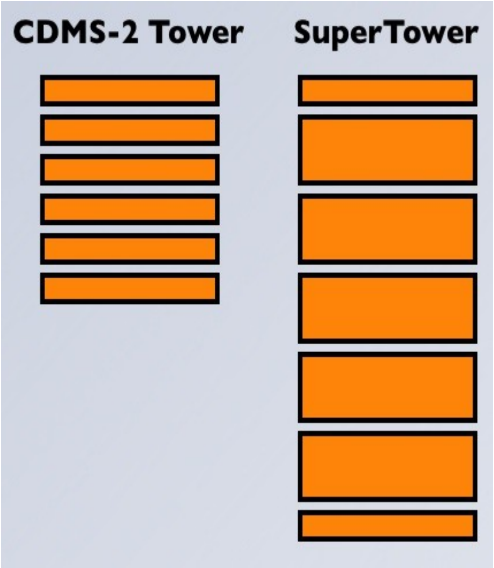
Phys. Rev. D 83, 112002 (2011)



SuperCDMS



- 2.5 times more massive Ge detectors (1-inch thick)
- reduced surface/volume ratio to decrease background
- endcap Ge veto detectors in each tower
- improved Al-fin layout for better phonon collection
- modified phonon-sensor layout with outter phonon guard ring similar to outter charge electrode
- first SuperTower data is currently analyzed to evaluate surface-event discrimination and detector contamination



Summary

- inelastic dark matter analysis including energies up to 150 keV

- improved surface-event rejection cut

- efficiency increased by ~1.5 compared to standard analysis

- weaker constraints on IDM parameter space due to occurance of three “high-energy“ events

- published in Phys. Rev. D 83, 112002 (2011)

- inelastic dark matter scenario now ruled out by XENON100 results Phys. Rev. D 84, 061101 (2011)